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GROUNDSPEED/AIRSPEED DIFFERENCES AS A WIND SHEAR INDICATOR AND --ETC(U)
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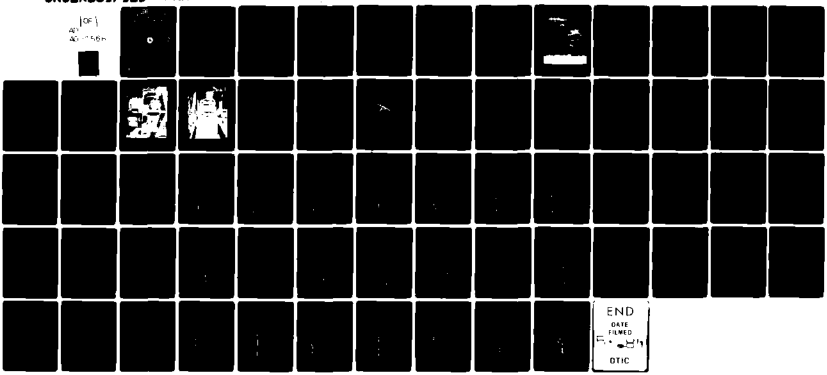

Report No. FAA-RD-81-1
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GROUNDSPEED/AIRSPEED DIFFERENCES AS A WIND SHEAR INDICATOR AND FLIGHT EVALUATION OF a DME-DERIVED SYSTEM TO DETERMINE GROUNDSPEED.

David M. Lawrence

FINAL REPORT

FEBRUARY 1981

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16. Abstract

The use of groundspeed in conjunction with airspeed as a wind shear indicator is discussed. It is shown that a satisfactory indication of headwind can be obtained using indicated airspeed and a low-cost groundspeed measurement device. This report describes the flight test and evaluation of a distance measuring equipment (DME) range-rate derived system for measuring airplane groundspeed. The system consists of a specially developed airborne unit operating in conjunction with unmodified very high frequency omnidirectional radio range (VOR)/DME ground stations. Operating at ranges up to 50 nautical miles in level flight directly toward or away from the ground station, the root mean square (RMS) groundspeed error is 3 to 5 knots. In landing approaches or climbout, the RMS error is 4 to 8 knots.

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METRIC CONVERSION FACTORS

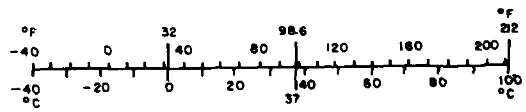
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

BACKGROUND.

The successful solution of the operational and flight path control problems caused when severe low-altitude wind shear occurs in a terminal area requires both ground-based and airborne detection systems. For the safest possible execution of a takeoff and climbout or approach and landing under such conditions, flight crews need accurate real-time information on the winds in their immediate airspace and on those that lie ahead of them. They also need information on airplane energy state and performance margins.

The simplest ground-based detection systems use anemometers to monitor surface winds above ground level (20 feet above ground level (AGL)) at several locations around the perimeter and near the center of an airfield. Such a system is used operationally to detect low-level horizontal wind shears but is limited, of course, in that it monitors only the shear at the 20-foot level. It is entirely a matter of statistical inference to estimate shear conditions existing above that level. The danger in this is clearly demonstrated in figure 1, a pictorial example of vertical wind shear. More advanced ground-based systems include existing airport surveillance radars modified to develop the capability of measuring wind speed and direction even beyond the range required for terminal operations. These will very possibly ultimately provide complete, real-time wind profiles along each approach path as needed.

Airborne equipment in its present stage of development uses aerodynamic and inertial inputs only. It, therefore, has no forward-looking capability and can develop information only on what is instantaneously happening to the airplane. Nevertheless, recent piloted flight simulator studies (references 1 and 2) reveal that one of the most promising aids to a pilot in making a landing approach through a severe wind shear is a groundspeed readout to complement the airspeed indicator. Low-cost, accurate, and responsive groundspeed systems are not yet commercially available. Accordingly, the Federal Aviation Administration (FAA) has undertaken a program to investigate the merits of several proposed systems and the merits of the airspeed/groundspeed technique as a means of detecting hazardous wind shears.

This report describes the test and evaluation of an airborne system designed to meet the needs for terminal operations. It is strictly a range-rate system and, accordingly, requires ground-based equipment (very high frequency omnidirectional radio range/distance measuring equipment (VOR/DME)) close to the runway centerline or centerline extended.

DISCUSSION

TECHNICAL DISCUSSION.

Airplane groundspeed per se is not important in flight dynamics since analytically it makes no difference whether an airplane is flying in a motionless airmass or in a uniformly moving airmass. At low altitude, however (0-2000 feet (ft.)), the atmosphere at times moves anything but uniformly, and the change in wind speed and direction that can occur between these altitude limits can be a serious hazard during climbout or landing approach.

Recognition of the existence of a wind shear condition can be achieved by a quick-response, real-time readout of wind speed and direction throughout the approach. Full solution of the wind triangle is possible only when accurate

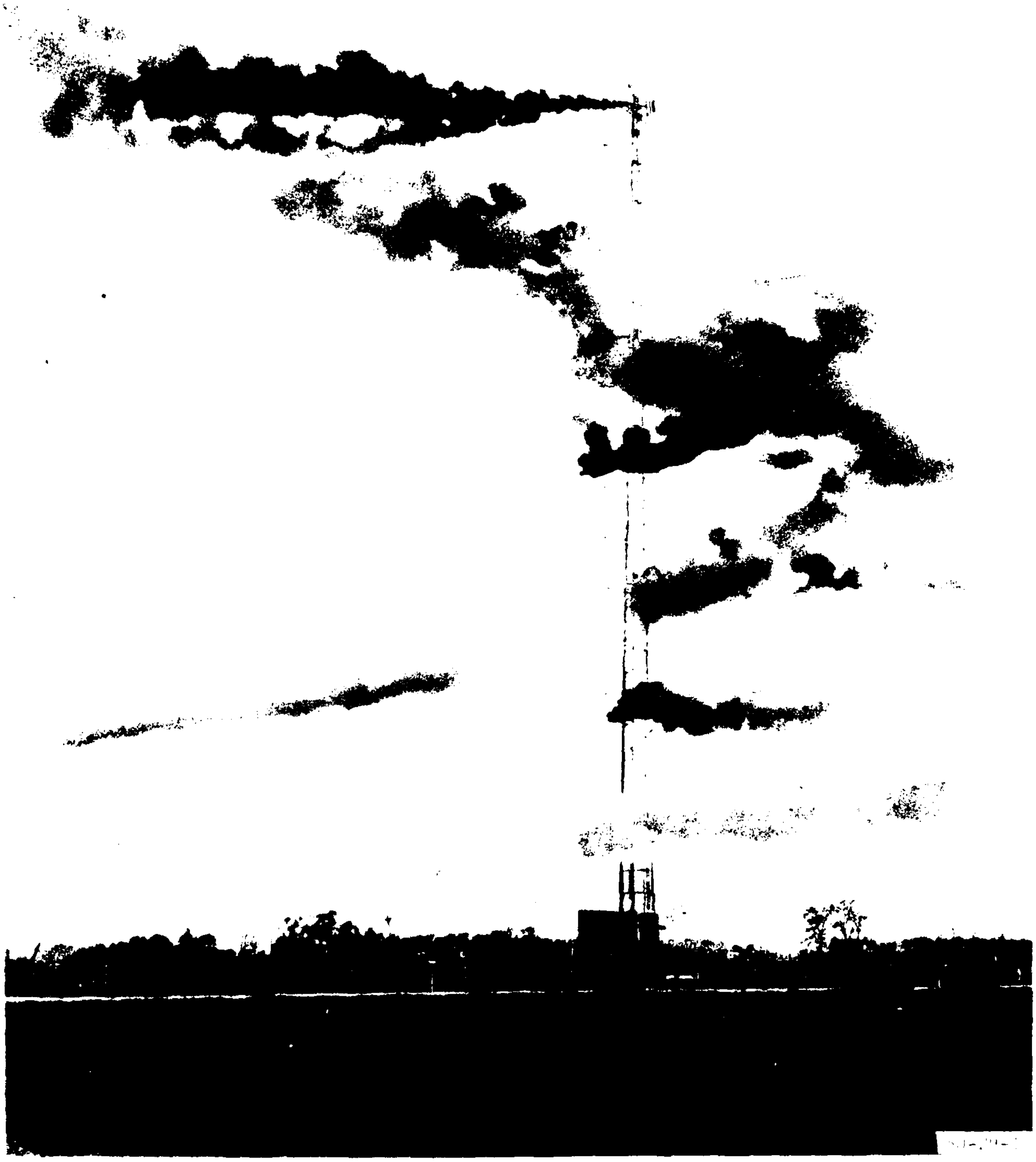

FIGURE 1. SMOKE STREAMS SHOWING 180° WIND DIRECTION CHANGE WITHIN 140 FEET OF GROUND. FLAT TERRAIN

information is available on groundspeed, track angle, true airspeed, and true heading — to provide which, a full navigation system is required. In most cases, a satisfactory approximation can be made, however, that does not require either track or heading information, thereby eliminating the need for the navigation system. The result obtained is a sufficiently accurate measurement of the headwind component only. Crosswind information is lost, but this is not considered to be too serious since it is well established that the majority of large commercial airplane landing accidents result from altitude or longitudinal position errors and not directional or lateral position errors. A numerical example will illustrate the validity of the headwind approximation:

An airplane is making an approach at 140 knots true airspeed (TAS) (figure 2). The headwind and crosswind are both 30 knots. The resulting groundspeed and drift angle are 106.75 knots and 12.37° respectively. The difference between the groundspeed and the true airspeed is 33.25 knots, which exceeds the actual headwind by 10 percent only. In most instances, the crosswind will obviously be much less than the 30 knots postulated in this example and the error in the approximation, correspondingly smaller. Thus, knowledge of the groundspeed in conjunction with true airspeed provides a satisfactory measure of the wind speed and a method for detecting wind shears.

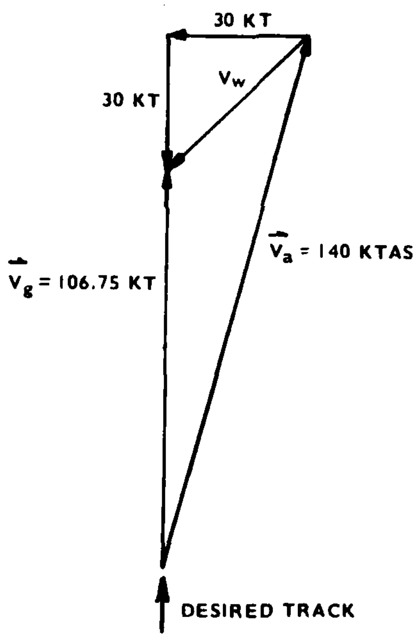

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FIGURE 2. APPROXIMATION TO HEADWIND USING GROUNDSPEED AND TRUE AIRSPEED

SYSTEM PERFORMANCE REQUIREMENTS.

Any groundspeed measurement system to be of value must be able to keep track of the accelerations that an airplane is capable of and the decelerations to which it can be subjected by the combined action of changes in wind speed and thrust deficiency. Estimates are presented here of the possible accelerations and decelerations calculated from hypothetical airplane lift, drag, and thrust data representative of a large jet transport airplane in the approach configuration.

LEVEL-FLIGHT ACCELERATION PERFORMANCE.

Airplane drag is given by:

$$D = \frac{1}{2} C_{D_o} \rho S V^2 + \frac{2KW^2V^{-2}}{\pi \rho b^2} \qquad (1)$$

where D = drag, pound

C_{D_o}	=	No-lift drag coefficient	(0.088)
S	=	Wing area, square feet	(5,500)
V	=	True airspeed, feet/ second (=140 knots)	(236.3)
K	=	Induced drag factor	(1.2)
W	=	Airplane gross weight, pound (lb.)	(550,000)
b	=	Airplane wing span, feet	(195)
ρ	=	Air density, slug/cubic feet	(0.00238)

At a typical approach speed of 140 knots indicated airspeed, under sea level standard conditions, this yields: D = 77,886 lb.

Typically, under sea level conditions, maximum thrust, T_{max}, is equal to one quarter of the the gross weight; so, in this case,

$$T_{max} = 137,500 \text{ lb. total.}$$

Therefore, the instantaneous level flight acceleration is given by:

$$\frac{dV}{dt} = \frac{\text{Excess Thrust}}{\text{Airplane Mass}} \qquad (2)$$

$$= \frac{1}{m}(T_{max} - D) \qquad (2)$$

$$\frac{dV}{dt} = \frac{G}{W}(137,500-77,886)$$
$$= 3.49 \text{ feet/second}^2$$
$$= 2.07 \text{ knot/second} \qquad (2)$$

On a 2.87° glide slope, the acceleration performance would be increased by 0.05g (0.95 knot/second). A corresponding decrease in acceleration occurs if the flight path is elevated 2.87°. It has been determined experimentally that 3 knots per second is indeed a typical acceleration performance figure for a commercial jet-transport airplane on a standard 3° approach.

EFFECT OF CHANGE OF AIRSPEED.

The drag expression (equation 1) can be written (using the listed airplane data)

$$D = 0.57596\ V^2 + 0.25532 \times 10^{10}\ V^{-2}$$

where V = True airspeed, feet/second

At three selected airspeeds, the corresponding drag values are

V kn	Drag, lb.	Level flight acceleration, knot/sec
120	85,866	1.79
140	77,887	2.07
160	77,013	2.10

It is evident from the preceding calculation that within a 20-knot band on either side of the nominal approach speed of 140 knots, the variation in drag is relatively small when compared with the total available thrust.

As indicated previously, a 3° glide slope by reason of the gravity component along the flight path increases the available acceleration by about 1 knot per second. Consequently, a reasonable upper limit for longitudinal acceleration in approach configuration on a 3° approach path is 3 knots per second. The maximum rate of airborne deceleration under any realistic set of conditions is considerably less, obviously, because there is no retroacting equivalent of the (T_{max}-D) term to cause it.

OPERATIONAL LIMITATIONS.

The system under test and evaluation in this report (VOR/DME range-rate) is not a pure groundspeed system, and some consideration should be given to the geometric differences between range-rate and true groundspeed. In figure 3, the ground station is at C, the airplane is at D, the airplane velocity vector is $\overrightarrow{DG}$, and the range vector to the ground station is $\overrightarrow{DC}$. The airplane groundspeed is the projection of $\overrightarrow{DG}$ in the horizontal plane; i.e., $\overrightarrow{DH}$. The problem is to establish the conditions under which the time rate of change of DC is an acceptable approximation for $\overrightarrow{DH}$.

First, define the radius vector $\overrightarrow{DC}$ (called R henceforth) in terms of cartesian coordinates with origin at C,

$$R^2 = x^2 + y^2 + z^2 \qquad (3)$$

(when flight path is not displaced out of the vertical plane containing the runway centerline)

$$R \frac{dr}{dt} = x \frac{dx}{dt} + y \frac{dy}{dt} + z \frac{dz}{dt}$$

$$\dot{R} = \frac{\dot{x}\,x + \dot{y}\,y + \dot{z}z}{\sqrt{x^2 + y^2 + z^2}} \qquad (4)$$

The airplane total velocity vector is given by

$$V_i^2 = \dot{x}^2 + \dot{y}^2 + \dot{z}^2 \qquad (5)$$

and the velocity vector in the horizontal plane is given by

$$V_g^2 = \dot{x}^2 + \dot{y}^2 \qquad (6)$$

And in general

$$\sqrt{\dot{x}^2 + \dot{y}^2} \neq \frac{\dot{x}x + \dot{y}y + \dot{z}z}{\sqrt{x^2 + y^2 + z^2}}$$

If the ground station is located at the side of the runway level with the glide slope interception point, if the airplane is at zero lateral displacement with respect to the runway centerline ($y=\dot{y}=0$), and the altitude z is held to $z = x \tan\gamma$ (and $\dot{z} = \dot{x} \tan\gamma$) then,

$$\dot{R} = \frac{\dot{x}x\,(1 + \mathrm{Tan}^2\gamma)}{R}$$

$$= \frac{1}{R}\,\dot{x}x\,\mathrm{Sec}^2\gamma \qquad (7)$$

For a 3° glide slope,

$$\mathrm{Sec}^2\gamma = 1.00275$$

and $$\frac{\dot{x}}{\dot{R}} = \frac{0.99726}{x}\sqrt{x^2\,\mathrm{Sec}^2\gamma + y^2} \qquad (8)$$

The ratio $\dot{x}/\dot{R}$ has been evaluated as a function of y and x and the results presented in table 1. It is evident that when $x \leq 5y$, the error in groundspeed measurements is equal to or greater than 2 percent and grows rapidly as x diminishes.

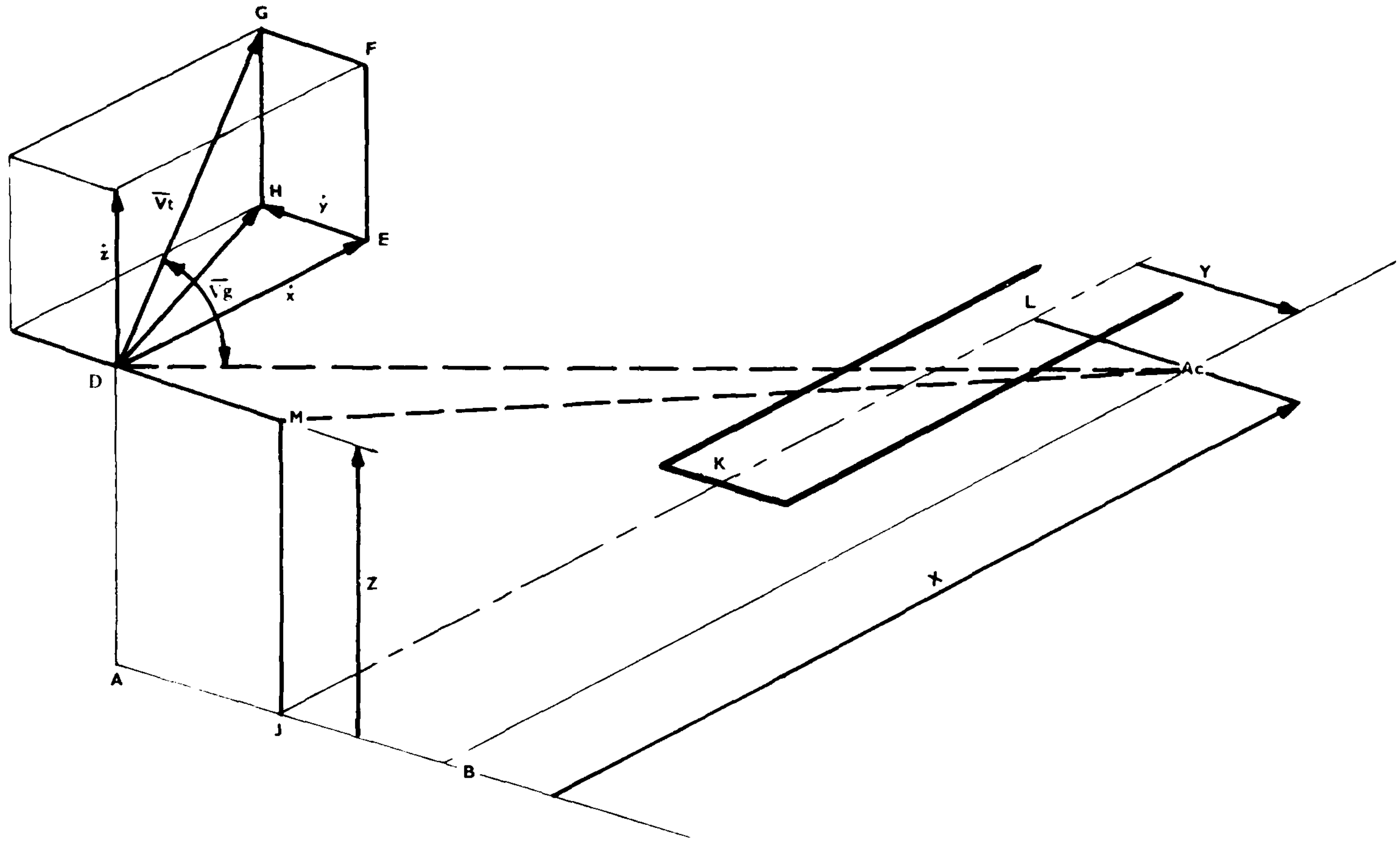

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FIGURE 3. VECTOR DIAGRAM PORTRAYING AIRPLANE POSITION AND VELOCITY VECTORS RELATIVE TO RUNWAY AND GROUND STATION

TABLE 1. RATIO OF GROUNDSPEED TO RANGE-RATE ($\dot{x}/\dot{R}$) VS. RANGE AND GROUNDSTATION LATERAL DISPLACEMENT

x, feet	y = 200	y = 400	y = 600	y = 1000
10,000	0.99883	0.99943	1.00042	1.00360
9,000	0.99888	0.99961	1.00084	1.00476
8,000	0.99894	0.99987	1.00143	1.00638
7,000	0.99904	1.00025	1.00228	1.00874
6,000	0.99918	1.00084	1.00360	1.01237
5,000	0.99943	1.00181	1.00578	1.01835
4,000	0.99987	1.00360	1.00977	1.02928
3,000	1.00084	1.0074	1.01835	1.05250
2,000	1.00360	1.01835	1.04248	1.11620
1,000	1.01835	1.07535	1.16417	1.41131
800	1.02928	1.11620	1.24767	1.59725
600	1.05250	1.19970	1.41131	1.93703
400	1.11620	1.41131	1.79860	2.68571
300	1.19970	1.66292	2.23055	3.47096
250	1.27819	1.88235	2.59340	4.11214

TEST ARTICLE.

A full description of the subject groundspeed system is given in reference 3. It was built in fulfillment of one of the primary objectives of a program that was undertaken to demonstrate the feasibility of using L-band DME as the basis for a groundspeed system. The full set of objectives of the program was:

1. To design and build an airborne L-band DME subsystem to derive groundspeed from either the Collins Radio 860-E2 DME or the King Radio KDM-7000 DME, accurate to within 2 knots (1σ), with a smoothing time no longer than 5 seconds.

2. To examine the characteristics of a modern DME transponder (Butler National Model 1066) and determine what modifications would be desirable to permit its use in the proposed groundspeed system.

3. Develop siting criteria for the ground (transponder) antenna to minimize the radio frequency (rf) multipath problem.

4. Examine the effects of situating the transponder antenna off the extended runway centerline, since no basic DME can output a true groundspeed when the airborne unit does not directly approach the transponder.

5. Investigate contributing subsystems and other factors that could affect system performance such as airplane airspeed measurement, ground anemometers, and airplane DME antenna placement.

6. Use the information developed in 1 through 5, above, to formulate an operational L-band DME wind shear warning system.

The candidate DME's both needed further work before being used in a groundspeed system. The Collins 860-E2 (which is used by 60 percent of the commercial airline fleet) does not output groundspeed, and the King KDM-7000, while it does output groundspeed, is heavily filtered to eliminate noise due to multipath phenomena and low signal strength at long range.

To give the selected DME (the Collins 860-E2) a groundspeed output, a microprocessor-controlled range tracker was built. This unit provides visual and digital output signals representing range, groundspeed, ambient wind, and wind shear magnitude. It has provisions for inputting airspeed and aircraft compass data. System parameters such as beacon delay and filter time constants can be changed by means of the hand-held controller.

While reference 3 describes ground antenna siting criteria, during the test and evaluation described in this report no changes were made to any of the antennas at the locations where test flights were made. In all cases, the transponders were existing operational units in daily use, and the antennas obviously had not been located with any reference to the criteria developed for use in a groundspeed system.

In summary, the airborne equipment for test (figures 4 and 5) consisted of a Collins 860-E2 DME receiver (not shown), the specially built microprocessor controlled range tracker, and the airplane DME antenna. The airplane used for the tests was the FAA Technical Center Grumman Gulfstream 1, N-47. Equipment for this evaluation consisted of an inertial navigation system (INS) to provide a groundspeed reference, a pressure transducer to measure altitude, and a Kennedy Model 9800 digital magnetic tape recorder.

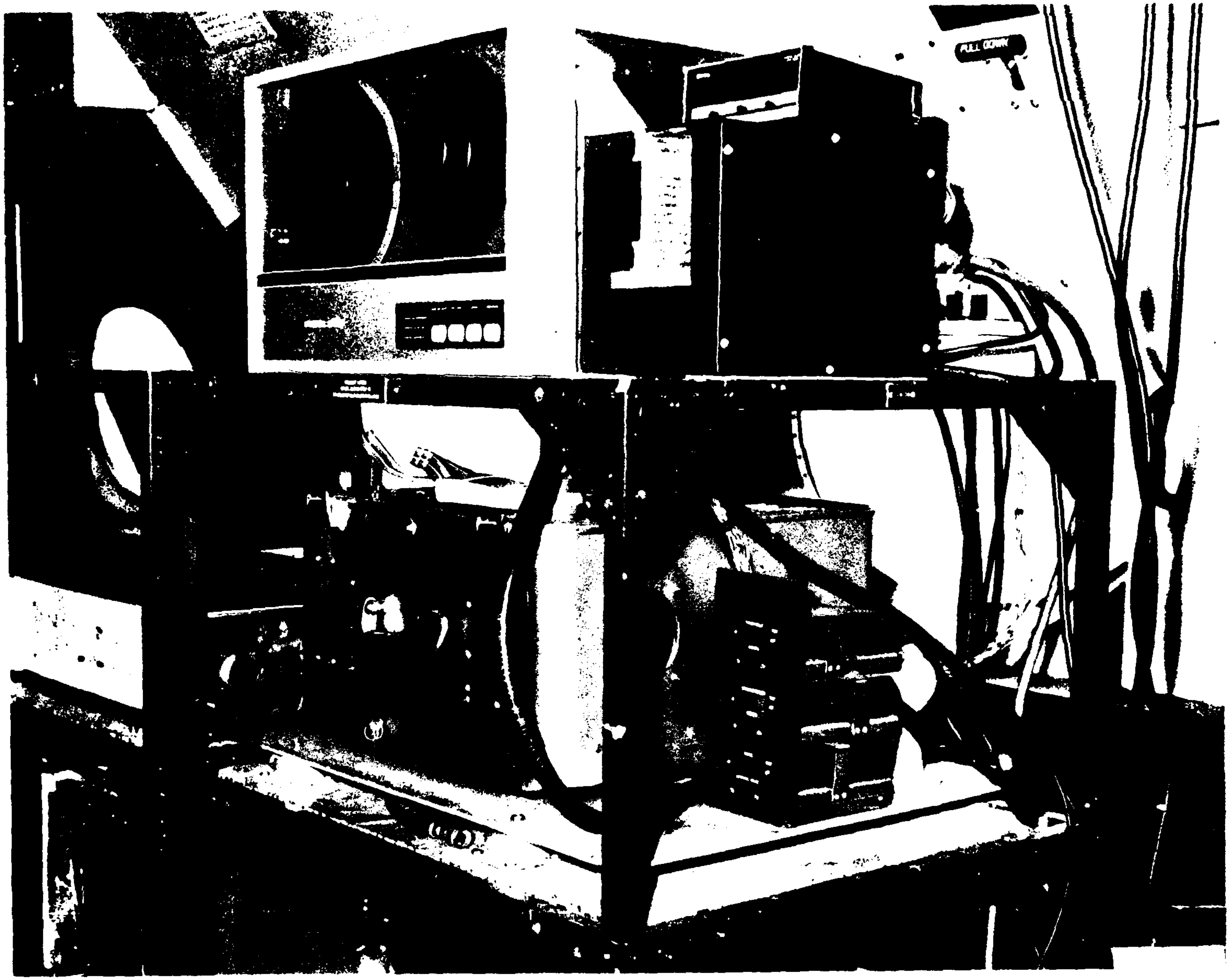


FIGURE 4. SIERRA DME RANGE-RATE SYSTEM INSTALLED IN GRUMMAN GULFSTREAM 1 TEST AIRPLANE

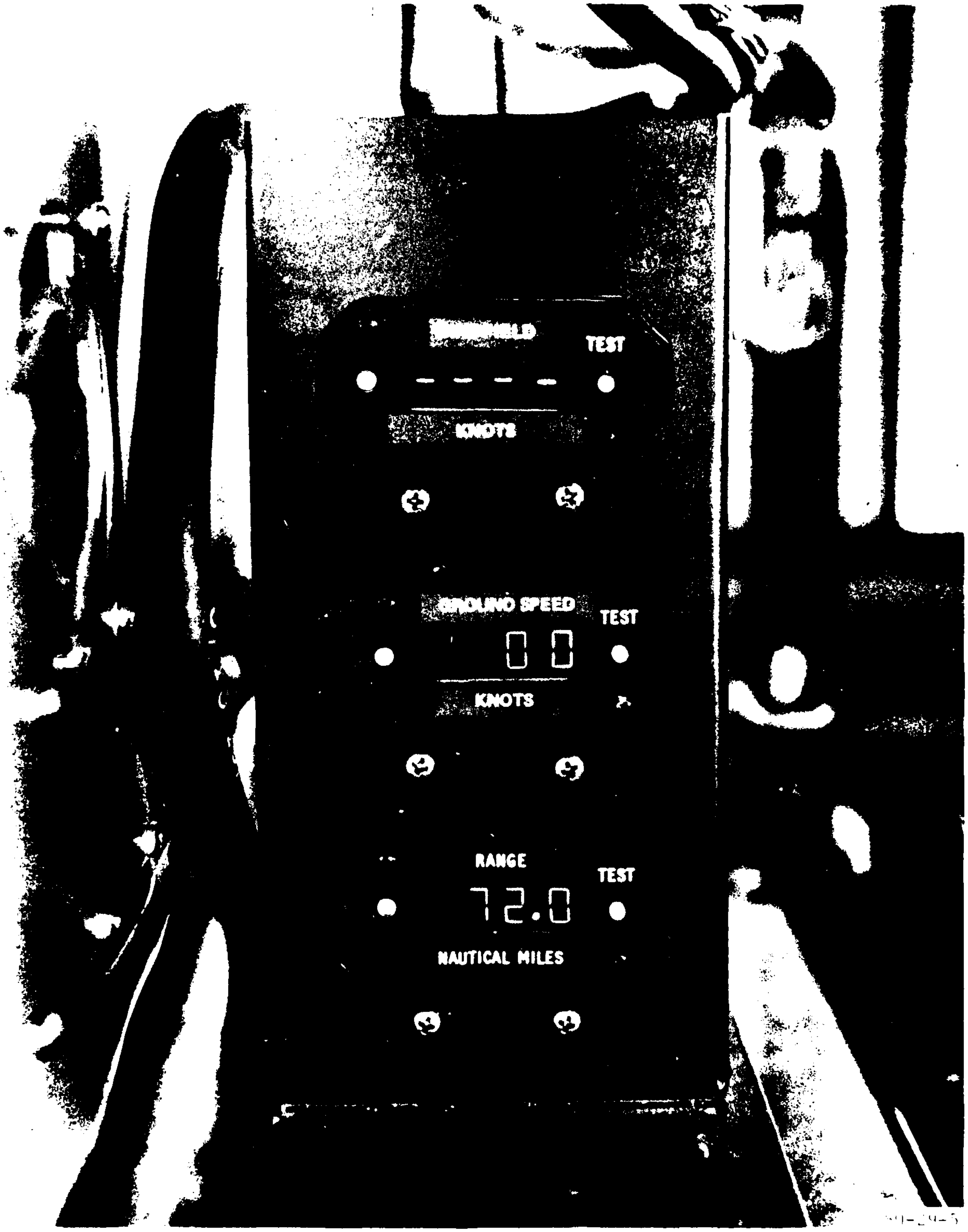


FIGURE 5. SIERRA DME DIGITAL DISPLAY

GROUNDSPEED REFERENCE.

An INS of a type in world-wide air-carrier use provided the groundspeed reference by which the test article was evaluated. The INS internal computer program was modified to provide a 5-second running average value of groundspeed with an update time of 1.4 seconds.

Since the INS is not primarily intended for the tracking of rapid transients in airplane groundspeed, some consideration should be given to how well it performs this secondary task as well as to its performance in the longer term navigation task and tracking of more slowly varying groundspeeds.

Information provided by the INS manufacturer indicates that under linear acceleration, the transient tilt of the inertial platform can be analyzed as a first order system with a time constant of 100 seconds. Such a system has linear velocity damping, and its equation of motion is:

$$m\ddot{x}a\cos\theta - mgb\sin\theta - k\dot{\theta} = 0 \qquad (9)$$

where:
- a = Effective moment arm of platform mass in longitudinal tilting
- b = Spring stiffness constant
- k = Damping moment coefficient
- m = Platform mass
- $\ddot{x}$ = Longitudinal acceleration
- θ = Platform tilt angle

Linearizing with the normal small angle approximations, the tilt response to a step input in longitudinal acceleration is:

$$\theta(t) = \frac{\ddot{x}a}{gb}\left(1-e^{-\frac{mgbt}{k}}\right) \qquad (10)$$

For this INS, the constants are such that under a 0.2g acceleration sustained for 100 seconds, the tilt angle rises to about 7°. Over a 10-second period, it is about 1°, which produces an erroneous acceleration signal of 0.0175g (0.56 feet/ second).

In most applications, sustained high accelerations will not occur. The most intensive longitudinal accelerations normally occur on the ground during takeoff and landing. Acceleration from rest to 100 knots in 2,500 feet represents a uniform acceleration of 5.70 feet/second^2 (0.18g or 3.4 knot/second), and requires about 30 seconds (These are typical figures for the test airplane.). Subsequent acceleration in the climbout is considerably less, and at no time during normal operations does the acceleration reach this figure. Descent through a uniform 6 knots per 100 feet wind shear at an approach speed of 130 knots and a 3° glide slope requires a mean acceleration of about 1 foot/second^2 to maintain the airspeed (for an initial headwind of 20 knots). However, at times considerably greater short-term accelerations would be required because of turbulent fluctuations of wind speed with respect to the mean.

In view of the above considerations, it is reasonable to accept the INS groundspeed as a test reference as long as satisfactory overall accuracy can be established. The determination of INS accuracy has been done during the course of the large number of flights in which an INS has been used in other projects. At the end of all flights, positional and groundspeed drifts are noted after the airplane has come to rest. The record shows that positional drift is consistently less than 1 nautical mile per hour, and groundspeed drift is less than 1 knot per hour.

EVALUATION/TEST PROCEDURES.

DME range-rate data were recorded during a series of normal approaches flown at the FAA Technical Center. During each approach the following variables were recorded:

DME range
DME range-rate
Airplane groundspeed (from reference INS)
Airplane track angle (from reference INS)
Pressure altitude

Data plots were prepared presenting:

DME range-rate vs. DME range and time
Airplane groundspeed vs. DME range and time
Track angle vs. DME range and time
Pressure altitude vs. DME range and time

Figure 6 shows the disposition of the VOR/DME ground stations with respect to the runways used in the tests. Logs for the flights are presented in table A-1.

DATA REDUCTION AND ANALYSIS.

Both groundspeed outputs (INS and test article) were digital and were recorded directly. Airplane track angle and true heading are digital outputs from the INS and were also recorded directly. Pressure altitude, recorded to show the descent or climbout profile, is output from a precision pressure transducer, signal conditioned (to lie between 0 and + 5 volts direct current (Vdc)) and digitized once per second.

Representative plots comparing INS- and DME- measured groundspeed are presented in appendix A. The range-rate approximation to groundspeed is valid over a limited portion of each test run; namely, after the airplane has gained the correct track and before it is in close enough for the ground station lateral offset to introduce large errors. For this equilibrium portion of each test run, the root mean square (RMS) difference between the INS reference groundspeed and the test article groundspeed was evaluated. These results are presented in table A-2.

TEST RESULTS.

The test data (test article groundspeed output, INS groundspeed output, track angle and range) are presented as functions of time and of range. Four sets of test runs were flown:

1. At St. Petersburg, Florida (SRQ) (figures A-1 through A-9)
2. Three sets at Atlantic City, New Jersey (ACY)

The logs for these flights are presented in table A-1. The St. Petersburg data were generated during level flight at altitude, at ranges up to 50 nautical miles from the VOR/DME ground station. The reason for this is simply that the primary purpose for the airplane's being in that area was to meet the needs of a different task. During the performance of that task it was possible at times to fly on a radial either toward or away from the ground station. The scatter in the groundspeed is attributable to a low signal-to-noise ratio resulting from the extreme ranges. The statistical summary (table A-2) shows that the mean error in most cases is half a knot or less, but the RMS error is quite large — as high as 5 knots. Figures A-10 through A-24 present results obtained locally on approaches to runways 04, 22, and 33 at ACY. During several of these, the airspeed was varied rapidly between 130 knots and 160 knots to determine system ability to track rapid acceleration and deceleration. Figures A-12 and A-16 demonstrate that system responsiveness matches that of the reference INS. During these local flights, data were recorded not only during flight toward or away from the ground station, but during the turn onto final approach and during flight past the ground station. (The location of the ground station with respect to the ACY runways is shown in figure 6.) Prior to turning onto the

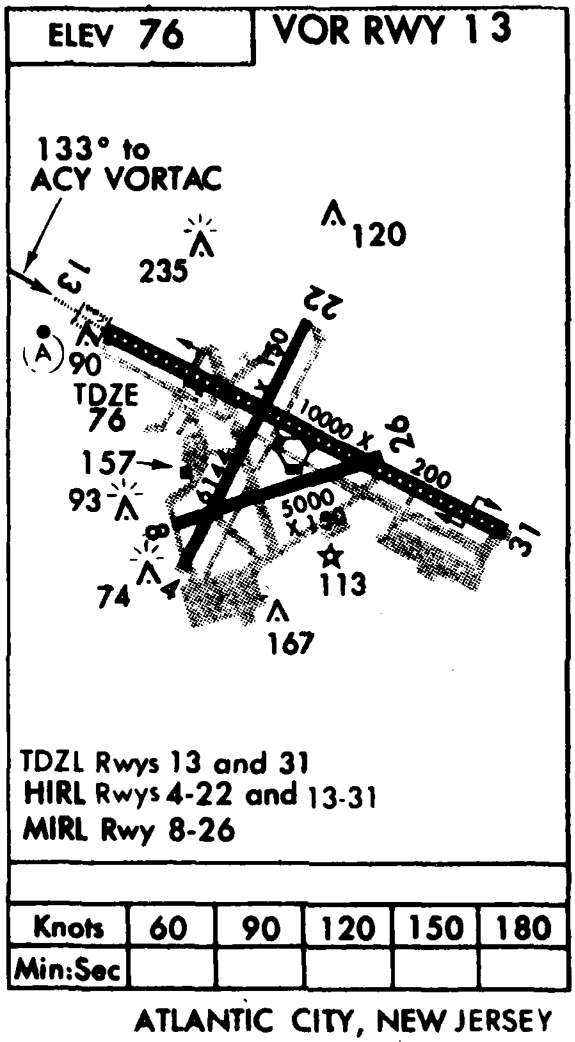


FIGURE 6. DISPOSITION OF VOR/DME GROUND STATIONS WITH RESPECT TO THE RUNWAYS USED IN THE TESTS

correct track, the range-rate may be anywhere between 0 and the actual groundspeed; e.g., the first 40 seconds in figure A-16, and again, at the end of the approach, the range-rate momentarily drops to 0 as the airplane passes abeam of the ground station (range ≈ 0).

The Atlantic City data still show an unacceptable amount of scatter (RMS groundspeed difference is consistently much higher than the 3-knot figure desired.). The reason for this is to be found in reference 3 (section 3.4, Antenna Siting Tests). It was found that to obtain a satisfactory antenna radiation pattern, free of scalloping, it was necessary to mount the antenna with its center of radiation approximately 4 feet above the ground. The normal height for the antenna radiation center is approximately 20 feet. At that height, the radiation pattern is heavily scalloped. This is believed to be the principal reason for the high scatter in the groundspeed system output. The FAA has no intention of changing the location or height of existing VOR/DME antennas since they were installed using a different (and still valid) set of criteria from those needed to obtain good performance with the current DME range-rate groundspeed system.

In determining the RMS error, care was taken to exclude from the computation those sections of the record in which the range-rate would predictably differ greatly from the true groundspeed. This difference would occur before turning into the approach path and at the end of the approach when the ground station lateral offset with respect to the runway centerline becomes a significant factor; i.e., when the range is equal to or less than five times the offset.

Figures A-25 through A-35 demonstrate system performance at ranges up to ±50 nautical miles. Figures A-36 and A-37 demonstrate the groundspeed dropout that occurred as the test airplane passed abeam and/or over the ground station.

CONCLUSIONS

1. In its present configuration, and using unmodified ground station antennas, the system does not meet the requirement of root mean square (RMS) groundspeed error equal to or less than 2 knots. System modification could probably improve near steady-state accuracy but may, at the same time, slow the response to transients.

2. The mean system output is very close to the reference groundspeed when the geometry of the flight is close to ideal. The mean difference, measured against the inertial navigation system (INS) groundspeed, is less than 2 knots for all but four of the test runs.

3. System ability to track rapid acceleration and deceleration approximately matches that of the reference INS (approximately 3 knots per second demonstrated). This figure is close to the maximum expected in normal flight operations.

REFERENCES

1. Gastrev, W.B., and Foy, W.A., Piloted Simulation Study of Low-level Wind Shear, Phase 4, Report under Contract DOT-FA75WA-3650, U.S. Department of Transportation (DOT), FAA, Stanford Research Institute International, Menlo Park, California, March 1979.

2. Kelley, W.W., Simulation Study to Evaluate a Constant Groundspeed Approach Method in Moderate And Severe Wind Shears, NASA TM 80060, NASA Langley Research Center, Hampton, Virginia, March 1978.

3. Anon., Final Report for L-DME Wind Shear Warning System, Sierra Research Corporation Technical Report Number TR-1819, Sierra Research Corporation, Buffalo, New York, May 1978.

APPENDIX

LIST OF ILLUSTRATIONS

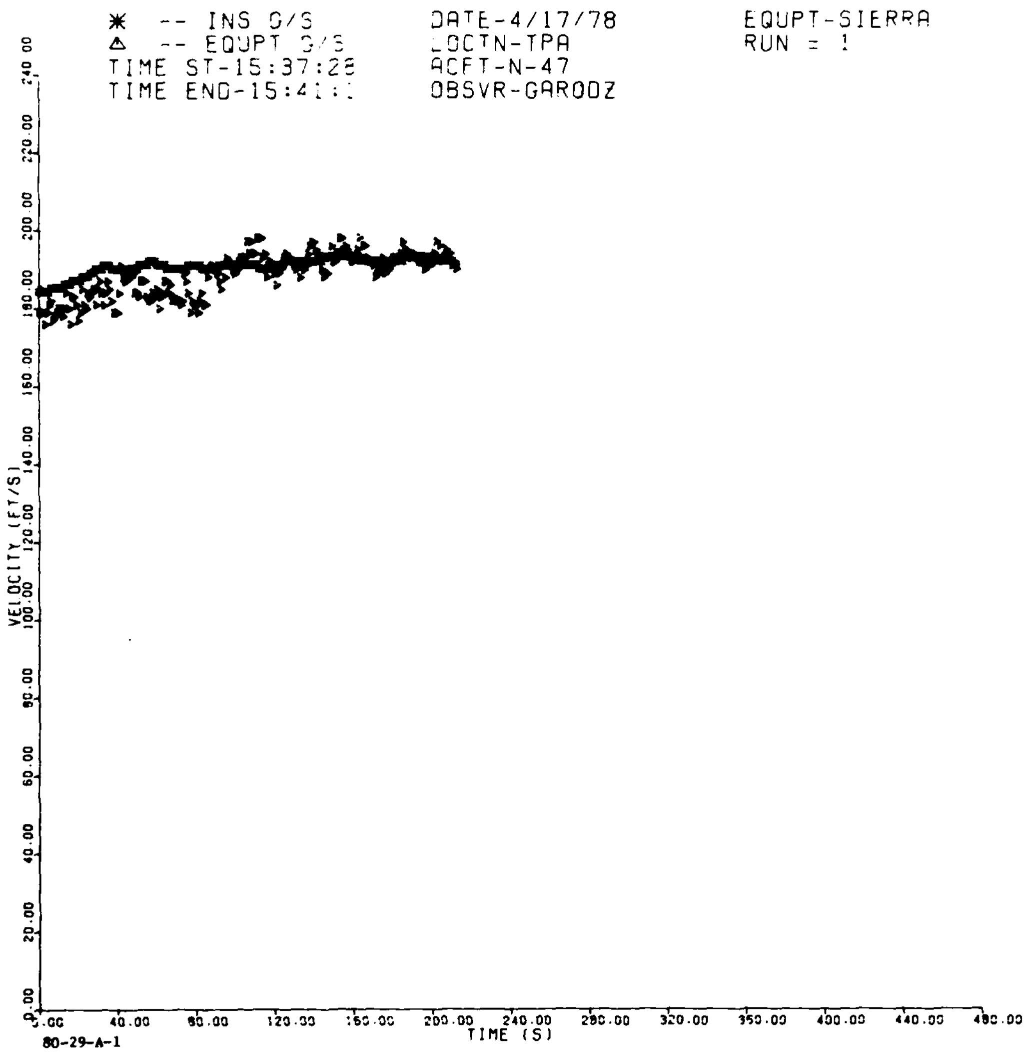
LIST OF ILLUSTRATIONS (Continued)

TABLE A-1. LOG OF DME GROUNDSPEED SYSTEM TEST RUNS

Location	Date	Run #	Runway	Start Time h/m/s	End Time h/m/s	IAS Knots	Acrft Config.	
SRQ	4-17-78	1	N/A	153728	154101	200	C	VOR 115.2 MHz, 012° RADIAL, OUTBOUND, 8500 feet ALT.
"	"	2	"	155040	155401	200	C	VOR 115.2 MHz, 012° RADIAL, OUTBOUND, 8500 feet ALT.
"	"	4	"	160249	160855	200	C	VOR 115.2 MHz, 012° RADIAL, INBOUND, 47-34 nmi, 8500 feet ALT.
"	"	5	"	161101	161633	200	C	VOR 115.2 MHz, 012° RADIAL, OUTBOUND, 40-48 nmi, 8500 feet ALT.
"	"	7	"	165842	170404	200	C	VOR 115.2 MHz, 032° RADIAL, OUTBOUND, 35-49 nmi, 8500 feet ALT.
"	"	8	"	170636	171241	200	C	VOR 115.2 MHz, 032° RADIAL, INBOUND, 46-? nmi, 8500 feet ALT.
"	"	9	"	171616	172057	200	C	VOR 115.2 MHz, 032° RADIAL, OUTBOUND ? - 45 nmi, 9500 feet ALT.
"	"	10	"	172401	173001	200	C	VOR 115.2 MHz, 032° RADIAL, INBOUND, 45-35 nmi, 9500 feet ALT.
"	"	11	"	173241	173731	200	C	VOR 115.2 MHz, 032° RADIAL, OUTBOUND, 9500 feet ALT.
ACY	5-5-78	1	04	142200	143211	130	PA	STANDARD APPROACH, 4000 feet - 50 feet, CLIMBOUT TO 4000 feet
"	"	2	22	143517	144207	130	PA	STANDARD APPROACH, 4000 feet - 50 feet, CLIMBOUT TO 4000 feet
"	"	3	04	144550	145721	130-160	PA	STANDARD APPROACH, 4000 feet - 50 feet, CLIMBOUT TO 3000 feet
"	"	4	22	145929	150740	130	PA	STANDARD APPROACH, 4000 feet - 50 feet
"	"	5	04	150925	151534	130	PA	STANDARD APPROACH, 4000 feet - 50 feet
ACY	5-25-78	1	31	101516	102025	130	PA	ILS APPROACH, 4000° - 50°
"	"	2	31	102646	103501	130	PA	ILS APPROACH, 4000° - 50°
"	"	3	31	104228	104643	130-160	PA	ILS APPROACH, 4000° - 50°
"	"	4	31	105414	110242	130	PA	ILS APPROACH, 4000° - 50°
"	"	5	31	110741	111507	130	PA	ILS APPROACH, 4000° - 50°
ACY	1-30-80	5	31	095335	100034		PA	ILS APPROACH, 4000° - 50°
"	"	6	31	101037	101700		PA	ILS APPROACH, 4000° - 50°
"	"	7	31	102245	102830		PA	ILS APPROACH, 4000° - 50°
"	"	8	31	103352	104120		PA	ILS APPROACH, 4000° - 50°
"	"	9	31	105340	110037		PA	ILS APPROACH, 4000° - 50°

TABLE A-2. STATISTICAL SUMMARY

Mean of Positive Differences (Knots)	Mean of Negative Differences (Knots)	Mean of All Differences (Knots)	RMS Difference (Knots)	Length of Record
2.414	-4.448	-2.344	4.933	3m 32s
2.483	-2.219	-0.277	2.953	3m 20s
3.330	-2.653	0.306	4.192	6m 05s
2.453	-2.641	-0.535	3.436	5m 30s
2.665	-2.267	0.347	3.341	4m 59s
2.516	-2.430	-0.492	3.171	6m 04s
2.465	-2.551	-0.286	3.188	4m 40s
3.452	-3.066	-0.314	4.305	5m 59s
2.959	-3.263	-0.192	4.318	5m 07s
3.919	-4.006	-0.228	5.240	3m 01s
3.627	-3.389	-0.846	4.525	5m 20s
3.436	-4.690	-1.620	5.798	3m 17s
3.552	-2.667	-0.041	4.354	3m 12s
3.298	-4.202	-1.169	5.289	4m 40s
4.266	-4.906	-1.783	7.139	6m 15s
2.593	-5.430	-3.591	6.452	3m 12s
4.338	-4.250	-0.720	5.401	4m 28s
3.775	-7.201	-3.918	8.168	5m 205
4.975	-3.912	-0.431	6.699	6m 00s
3.636	-3.521	-1.023	4.515	5m 40s
4.147	-4.274	-0.917	5.618	5m 00s
8.248	-5.064	2.279	10.928	5m 40s
4.856	-3.826	1.149	6.254	6m 30s



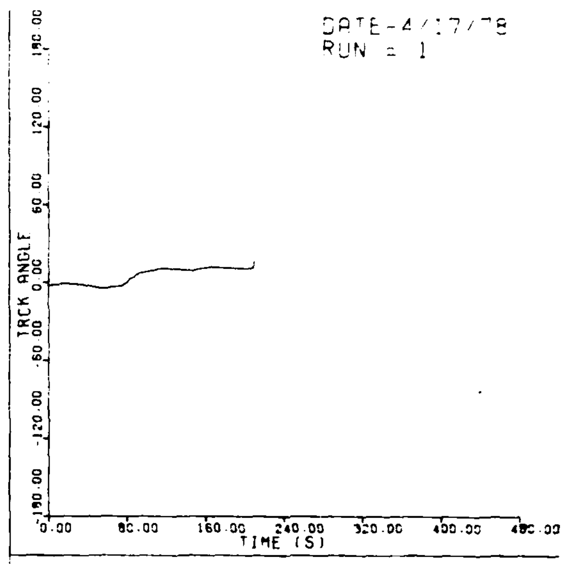


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FIGURE A-1. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, TIME), RUN 1

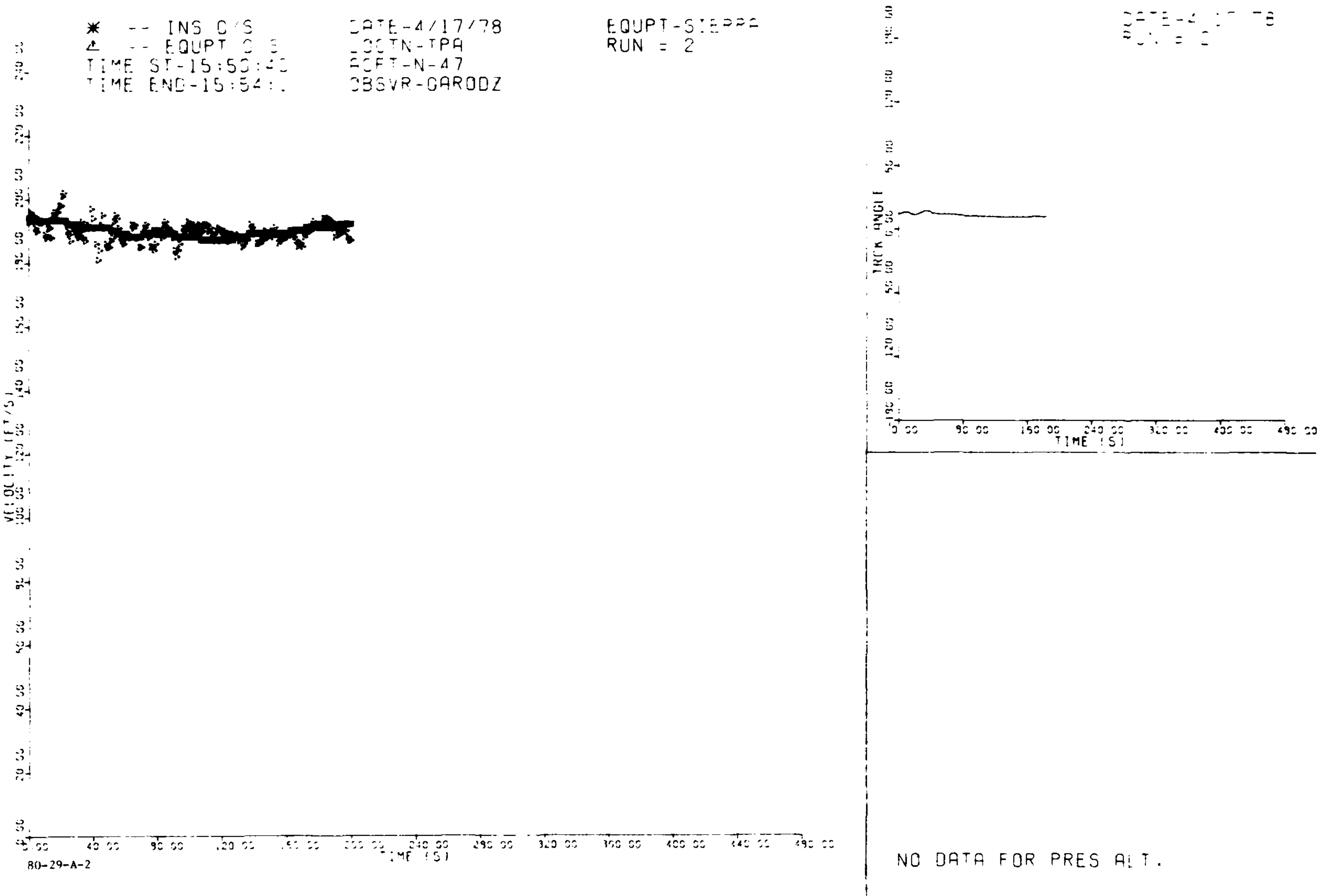


FIGURE A-2. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, TIME), RUN 2

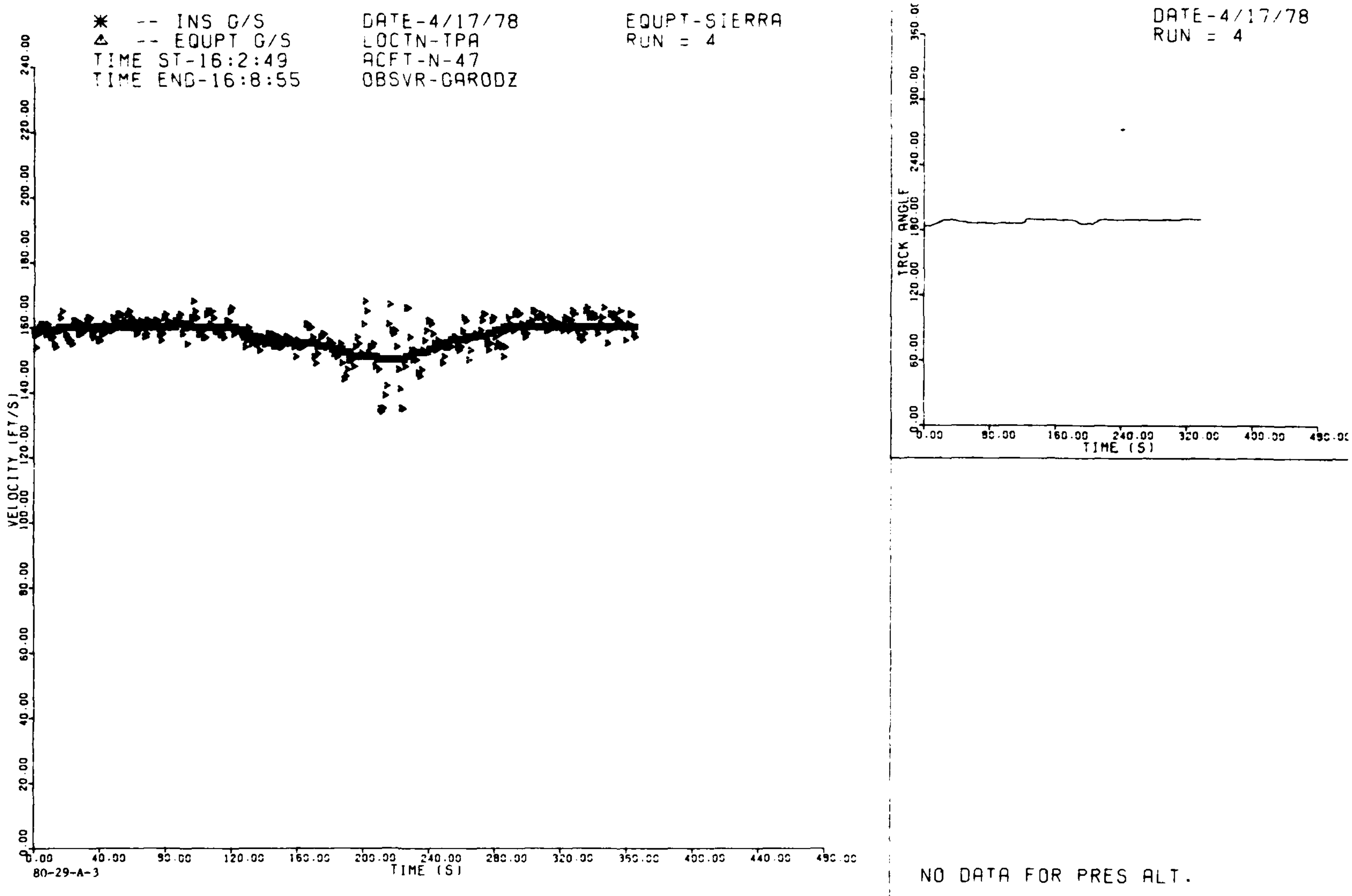


FIGURE A-3. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, TIME), RUN 4

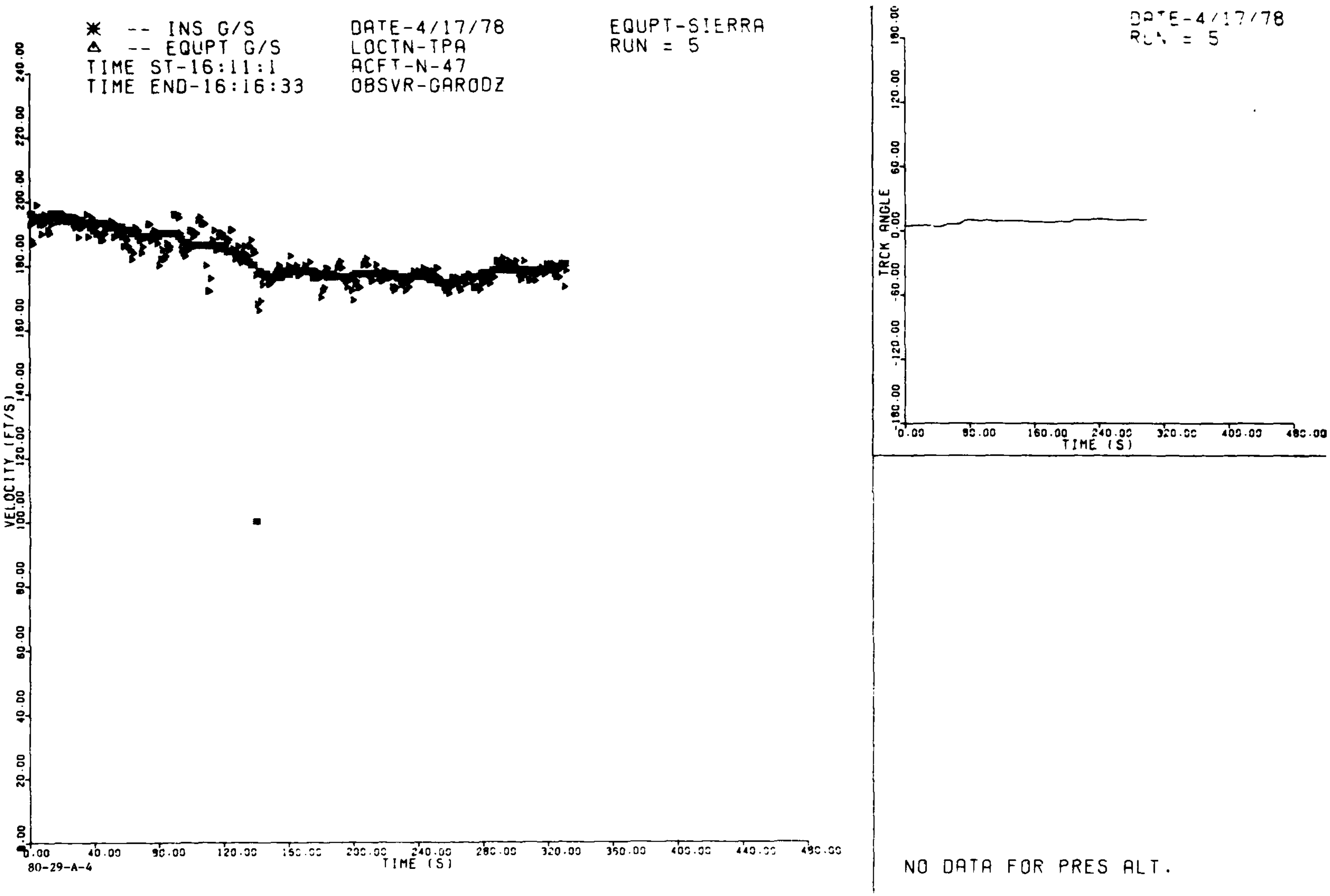


FIGURE A-4. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, TIME), RUN 5

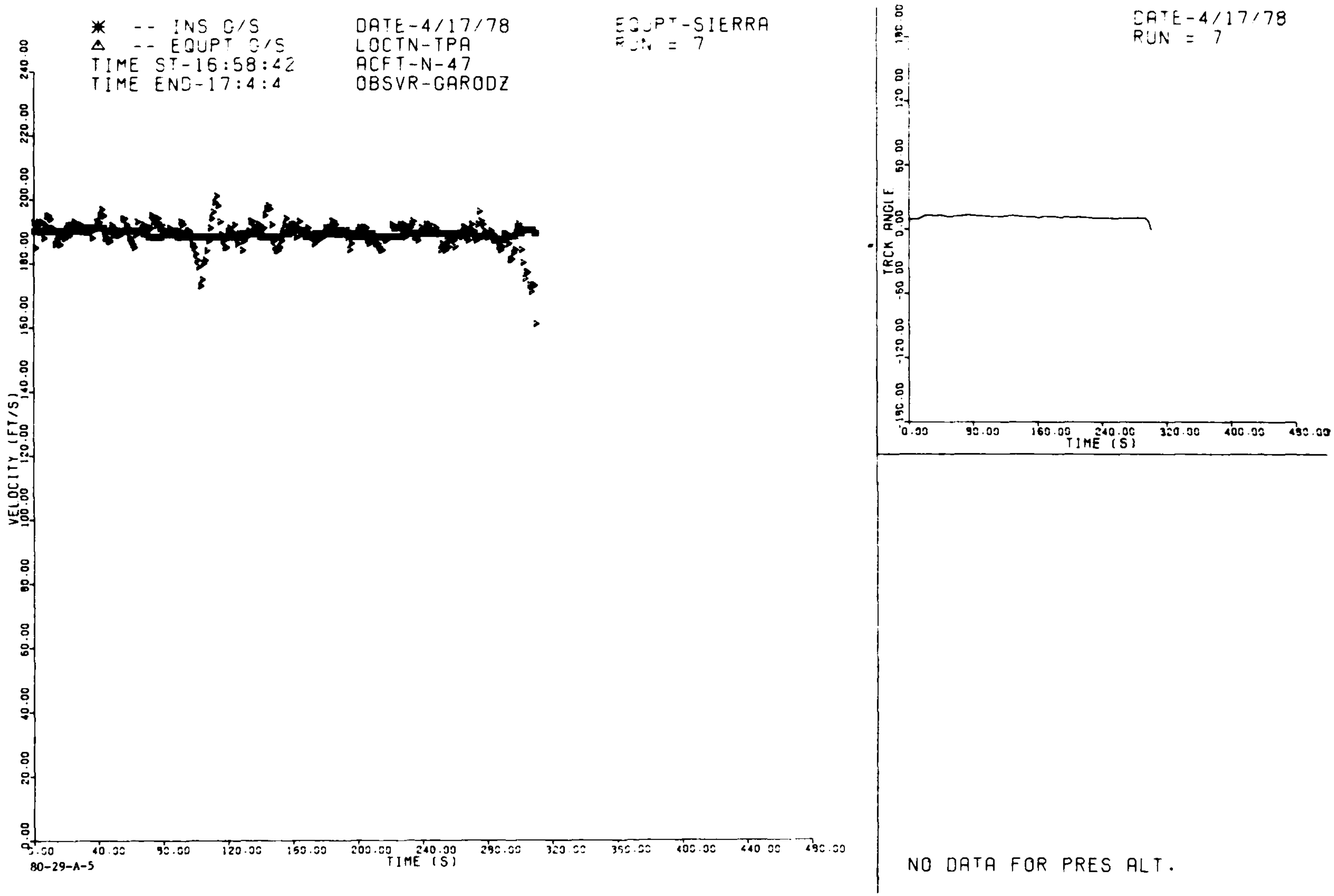


FIGURE A-5. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, TIME), RUN 7

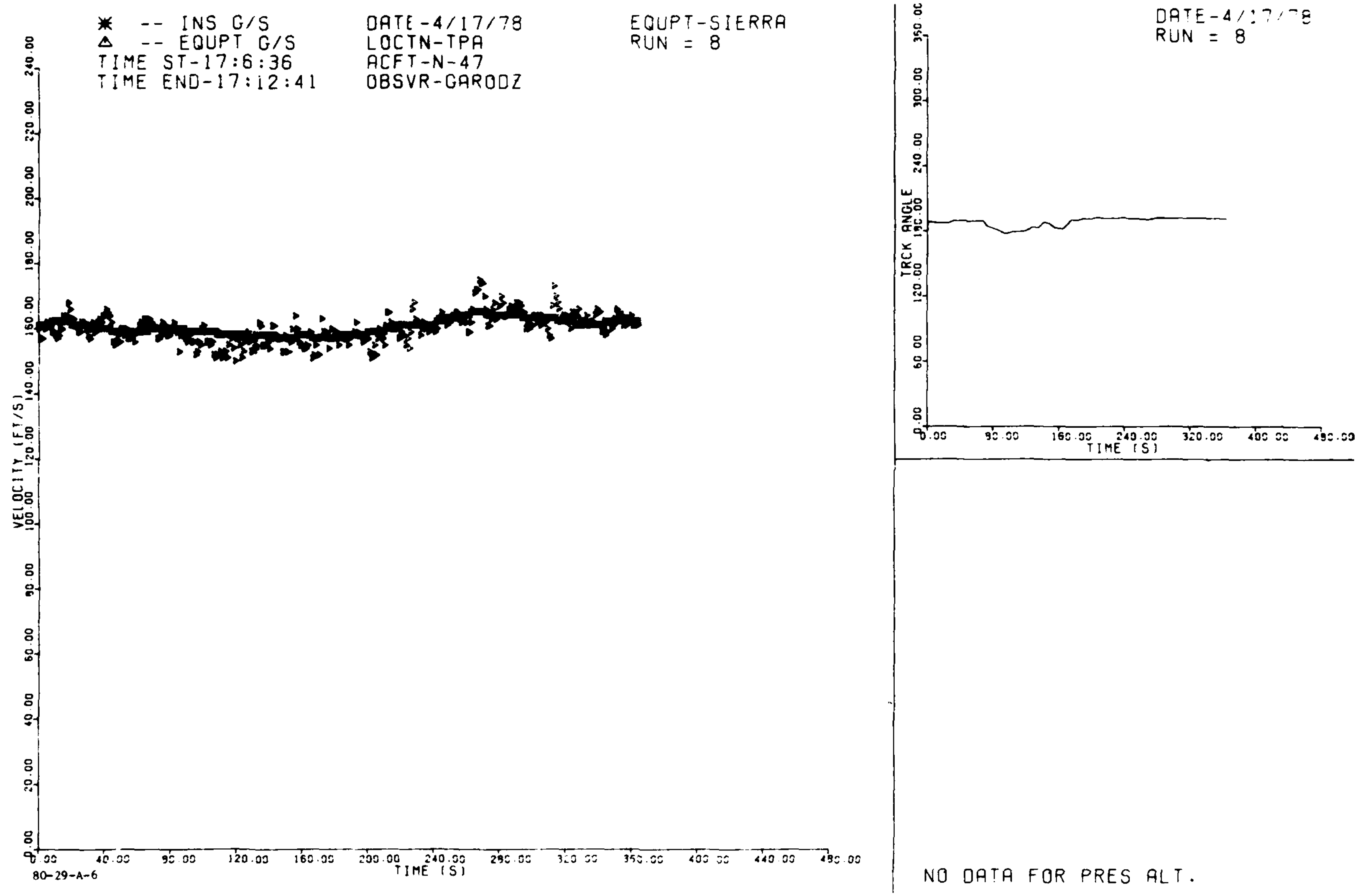
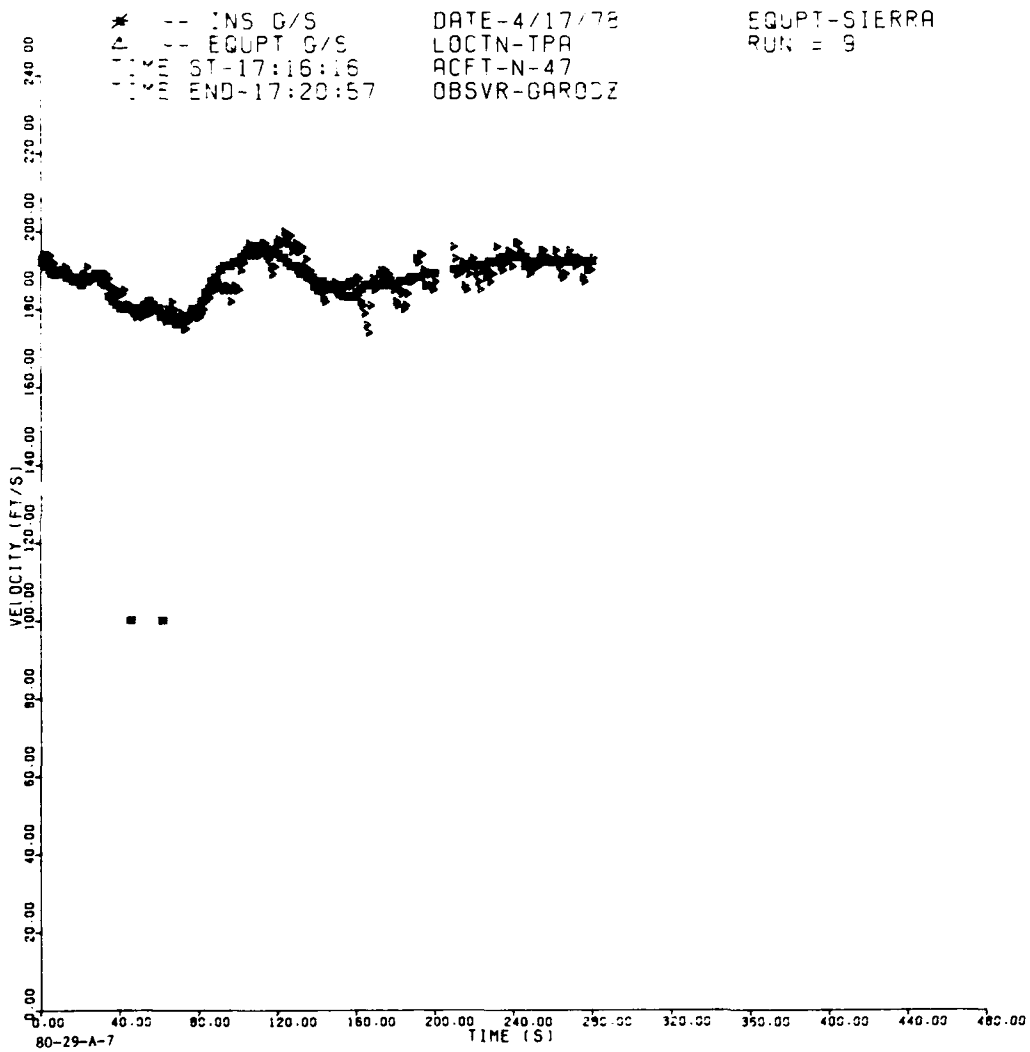
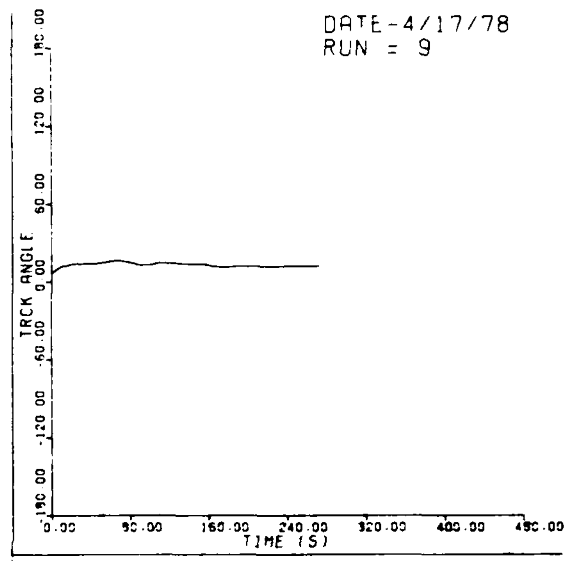


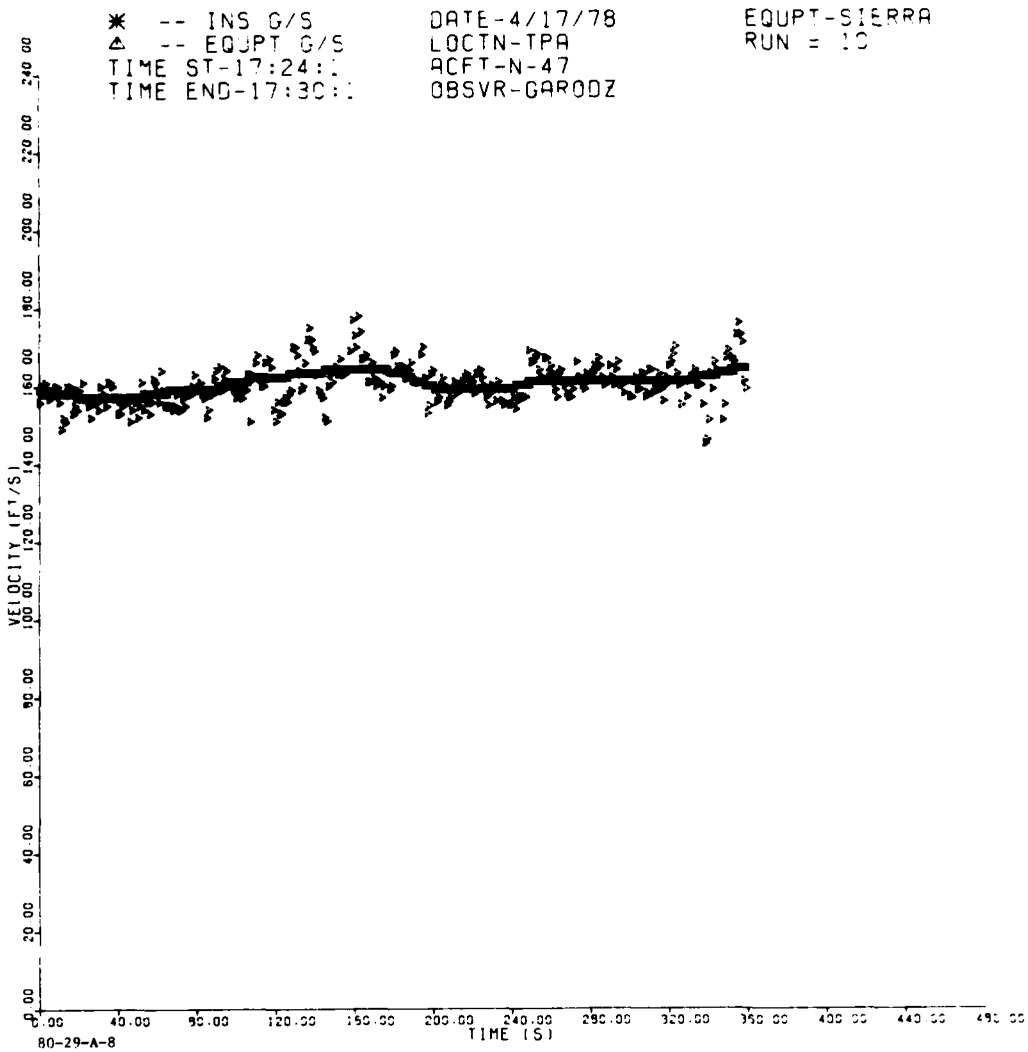
FIGURE A-6. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, TIME), RUN 8





NO DATA FOR PRES ALT.

FIGURE A-7. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, TIME), RUN 9



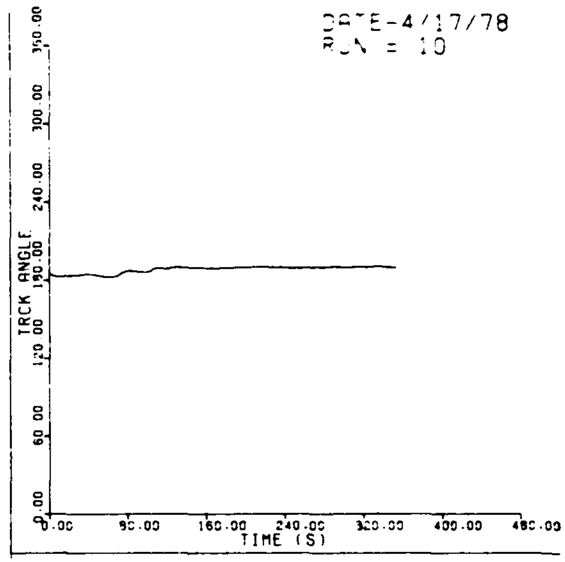


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FIGURE A-8. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, TIME), RUN 10

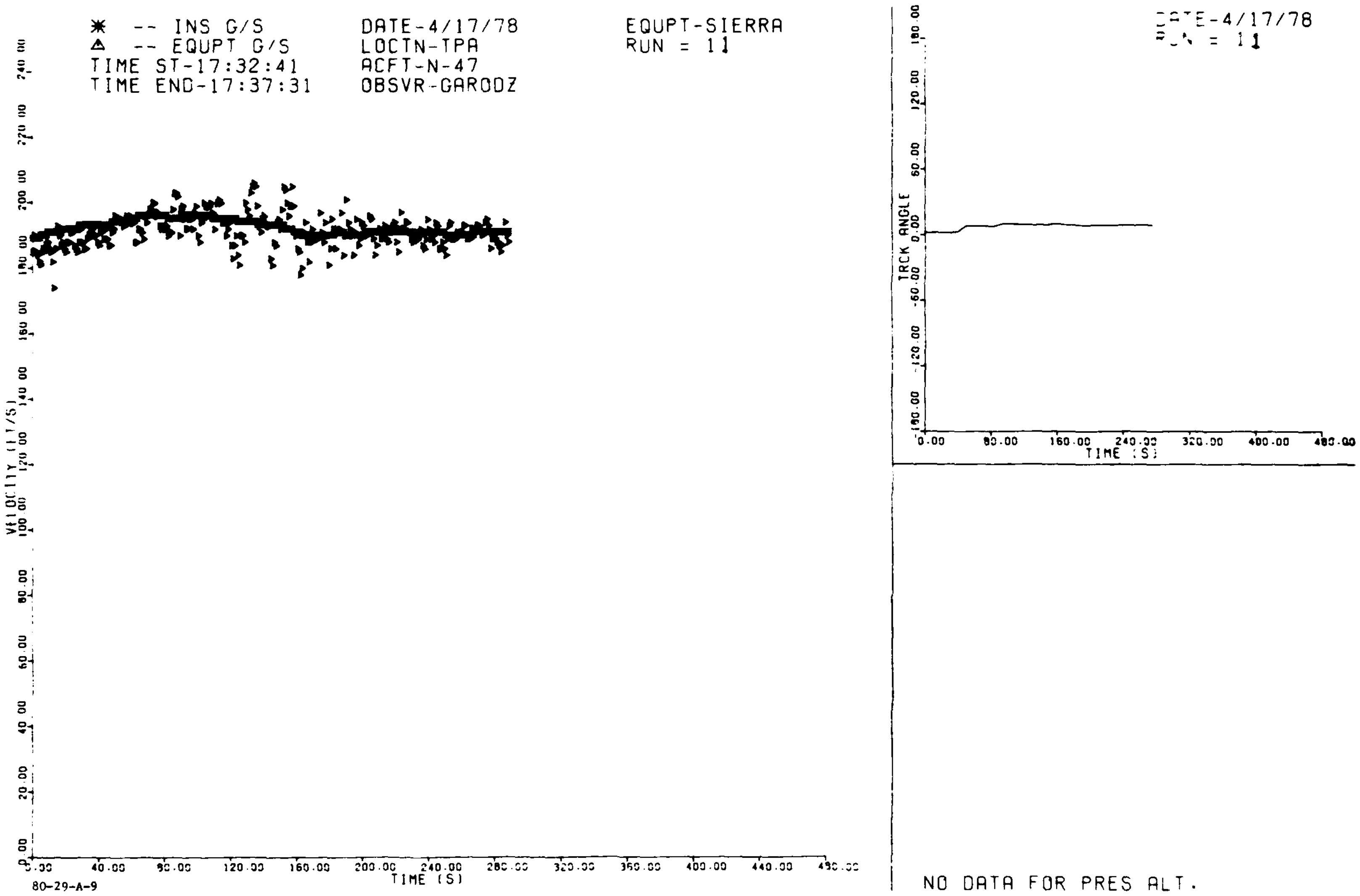


FIGURE A-9. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, TIME), RUN 11

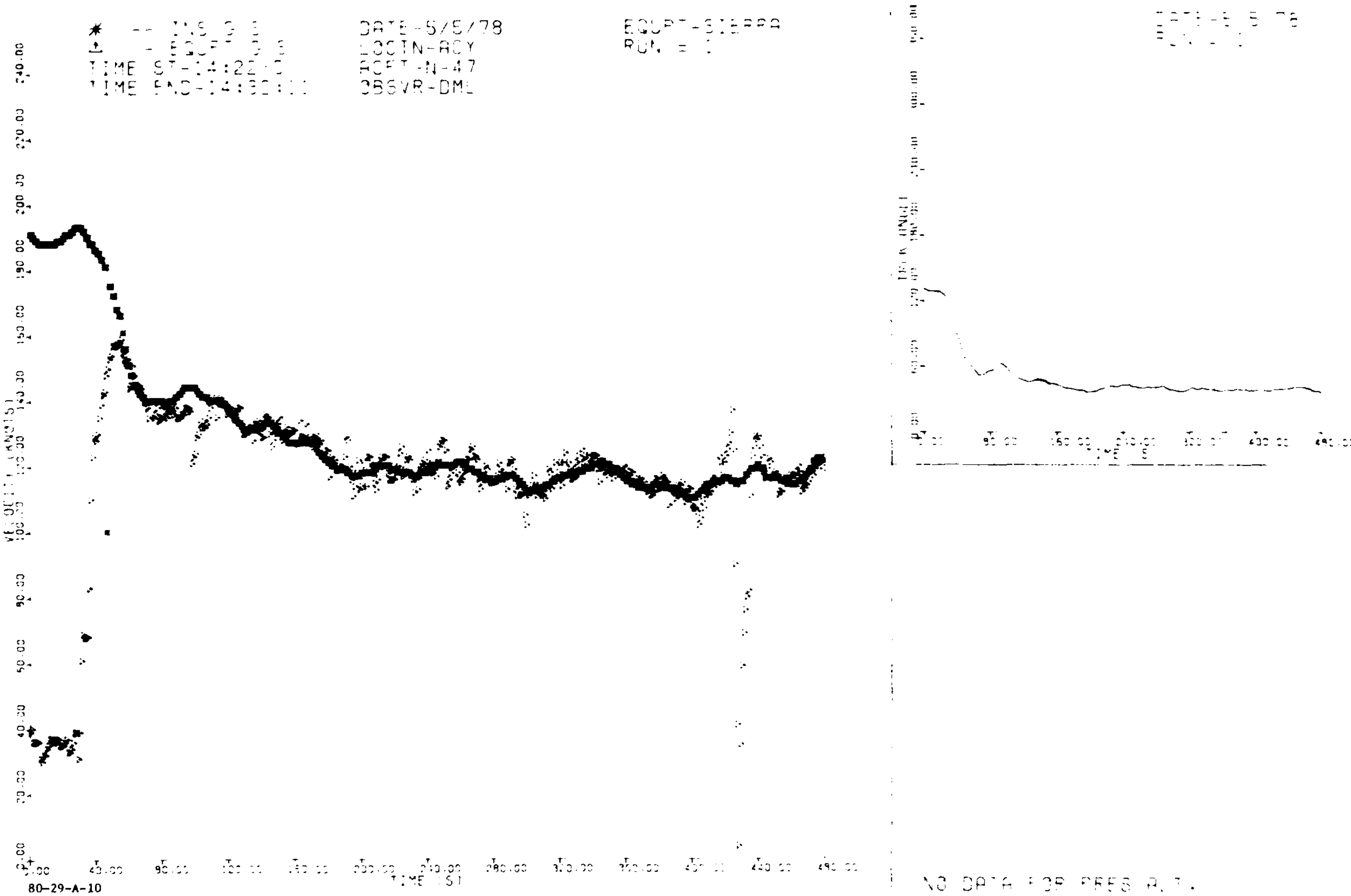


FIGURE A-10. DME AND INS GROUNDSPEED TIME HISTORY (5/5/78, ATLANTIC CITY, TIME), RUN 1

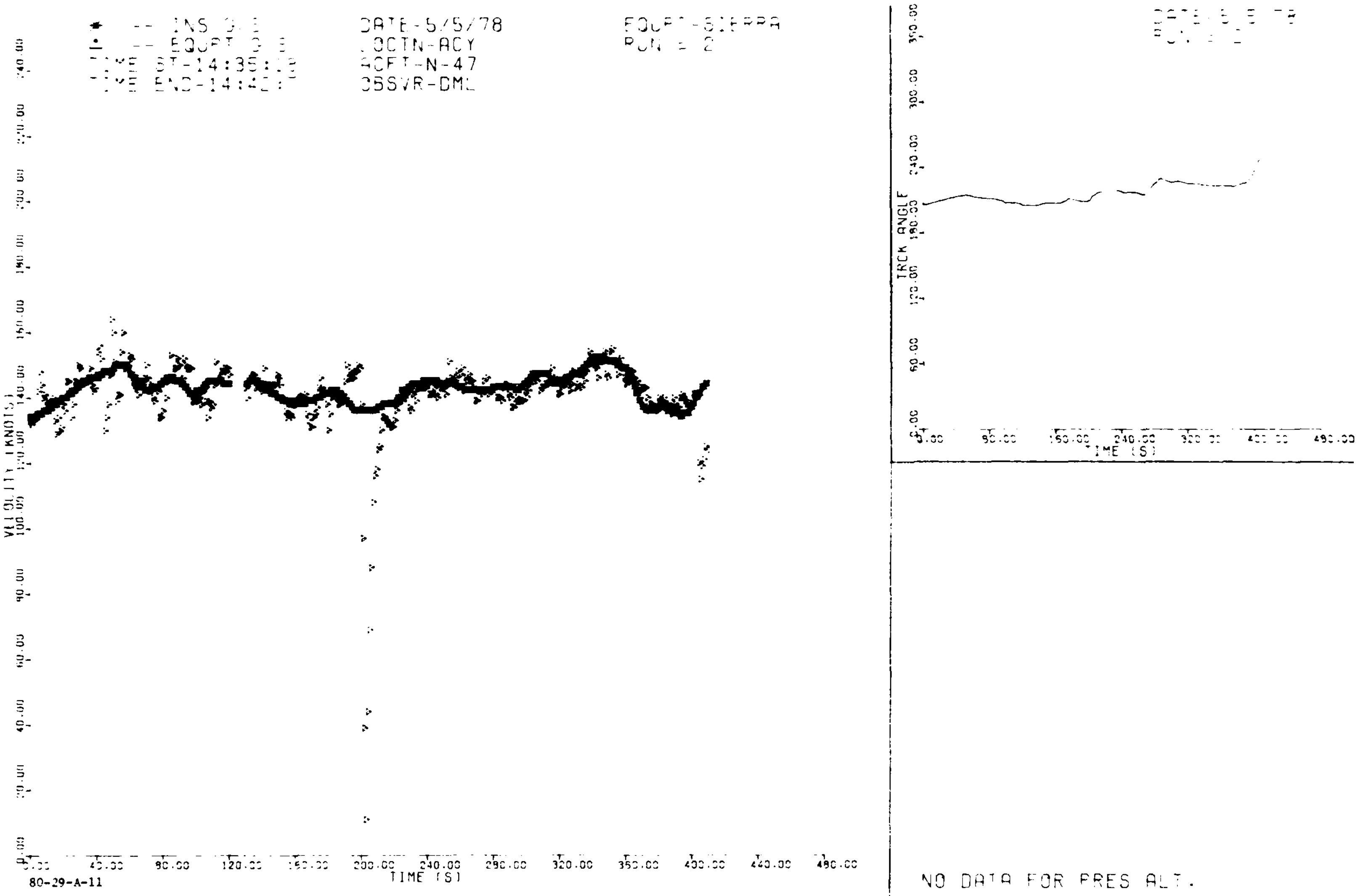


FIGURE A-11. DME AND INS GROUNDSPEED TIME HISTORY (5/5/78, ATLANTIC CITY, TIME), RUN 2

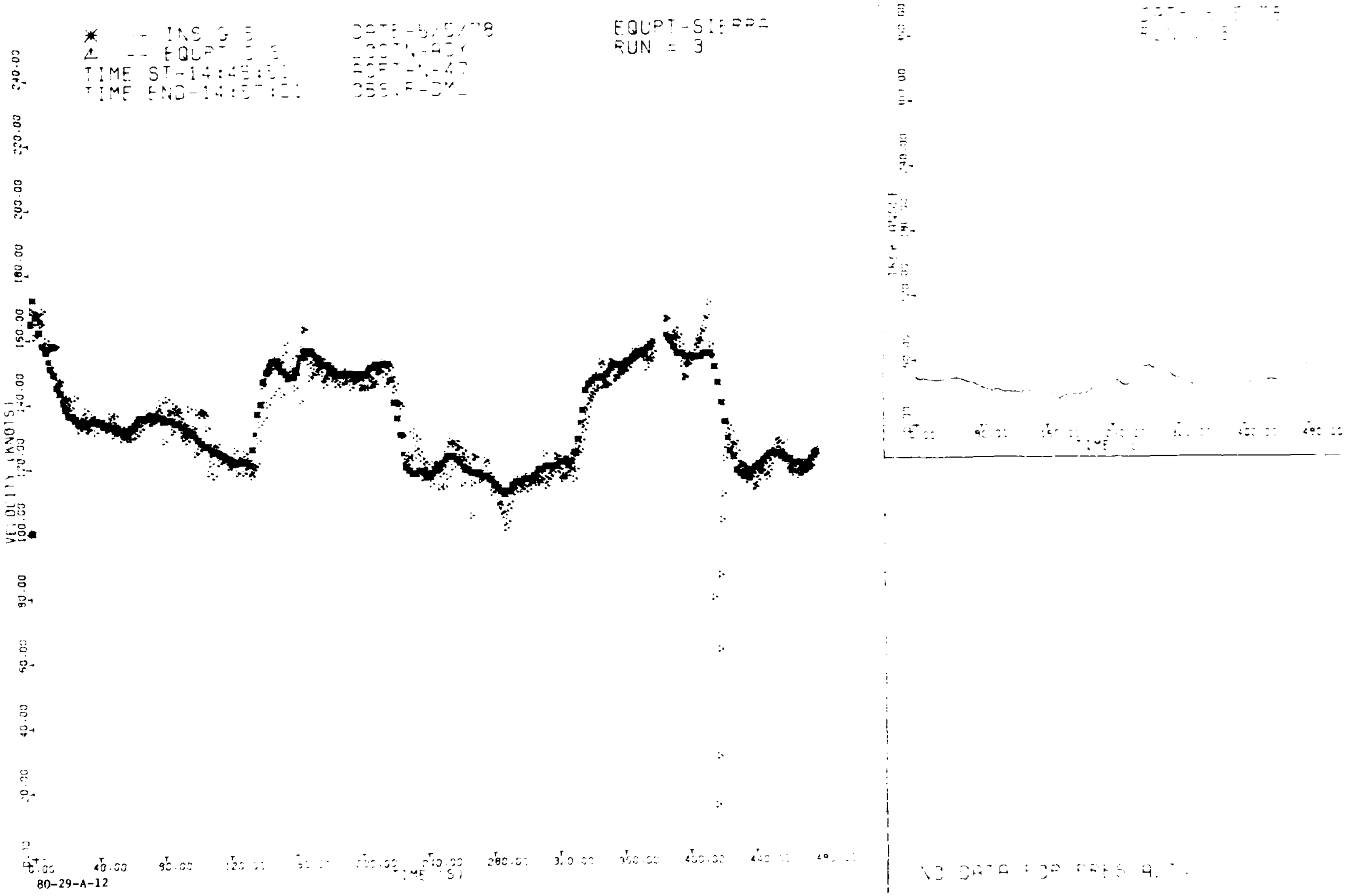


FIGURE A-12. DME AND INS GROUNDSPEED TIME HISTORY (5/5/78, ATLANTIC CITY, TIME), RUN 3

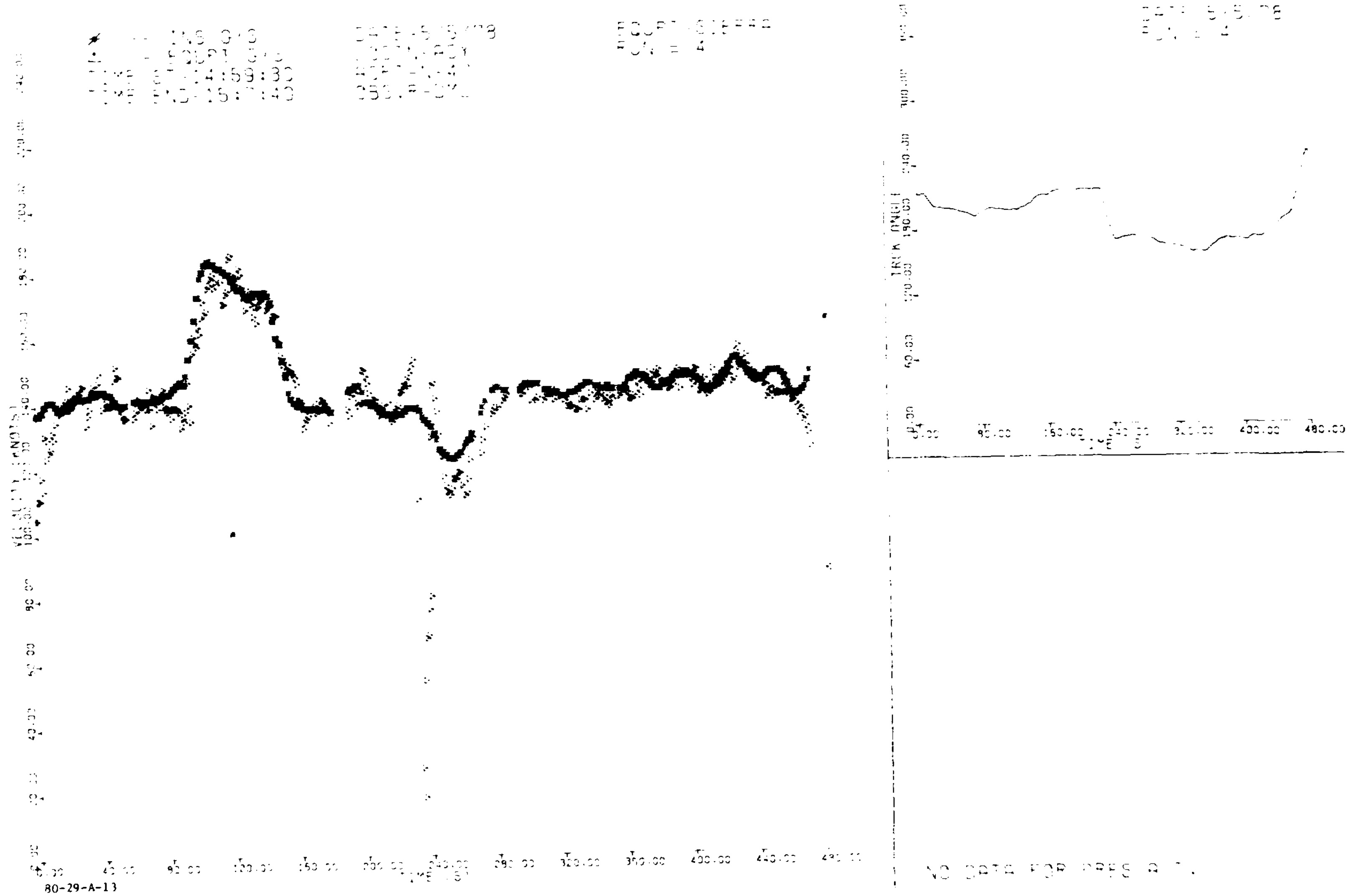


FIGURE A-13. DME AND INS GROUNDSPEED TIME HISTORY (5/5/78, ATLANTIC CITY, TIME), RUN 4

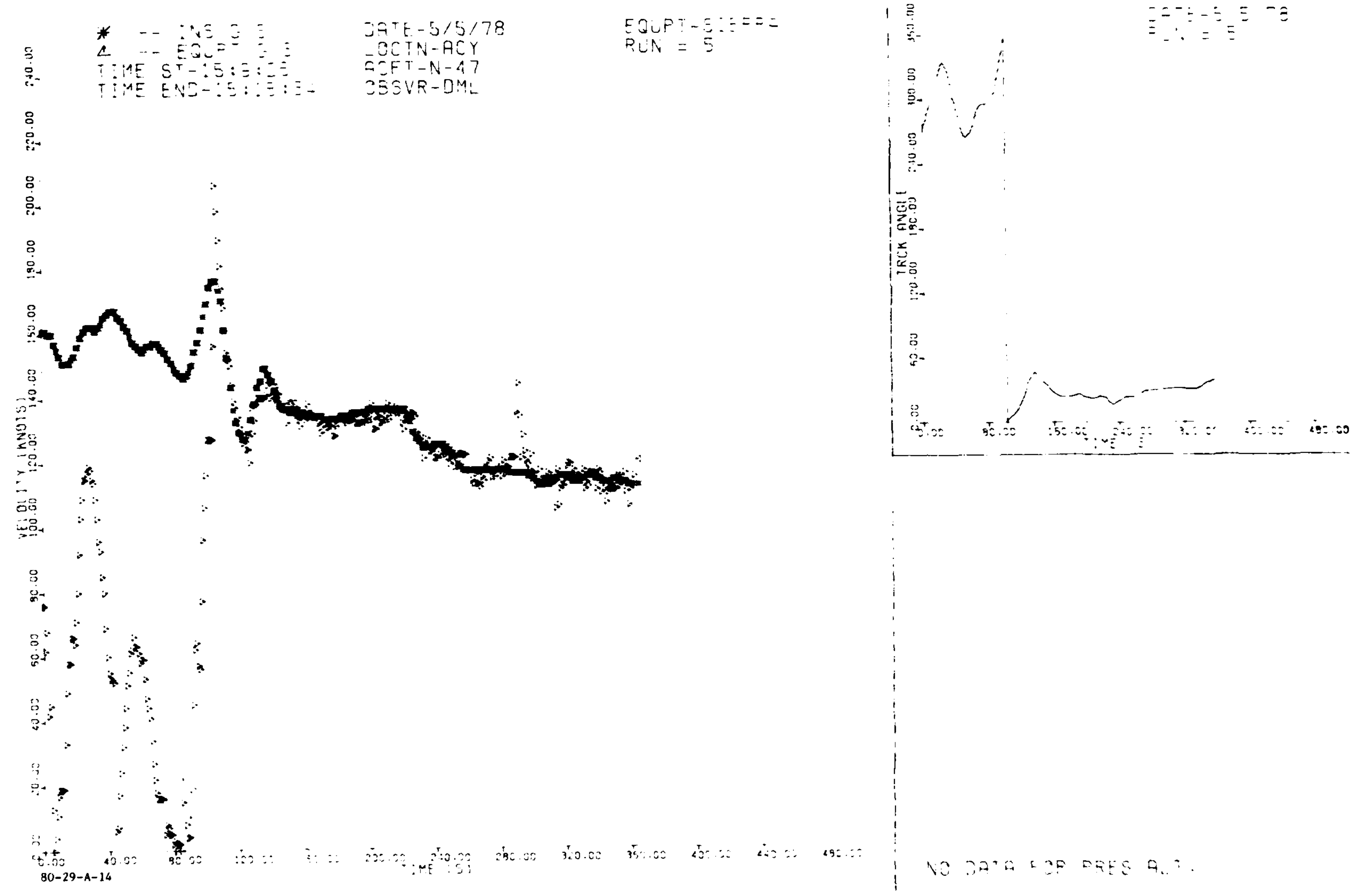


FIGURE A-14. DME AND INS GROUNDSPEED TIME HISTORY (5/5/78, ATLANTIC CITY, TIME), RUN 5

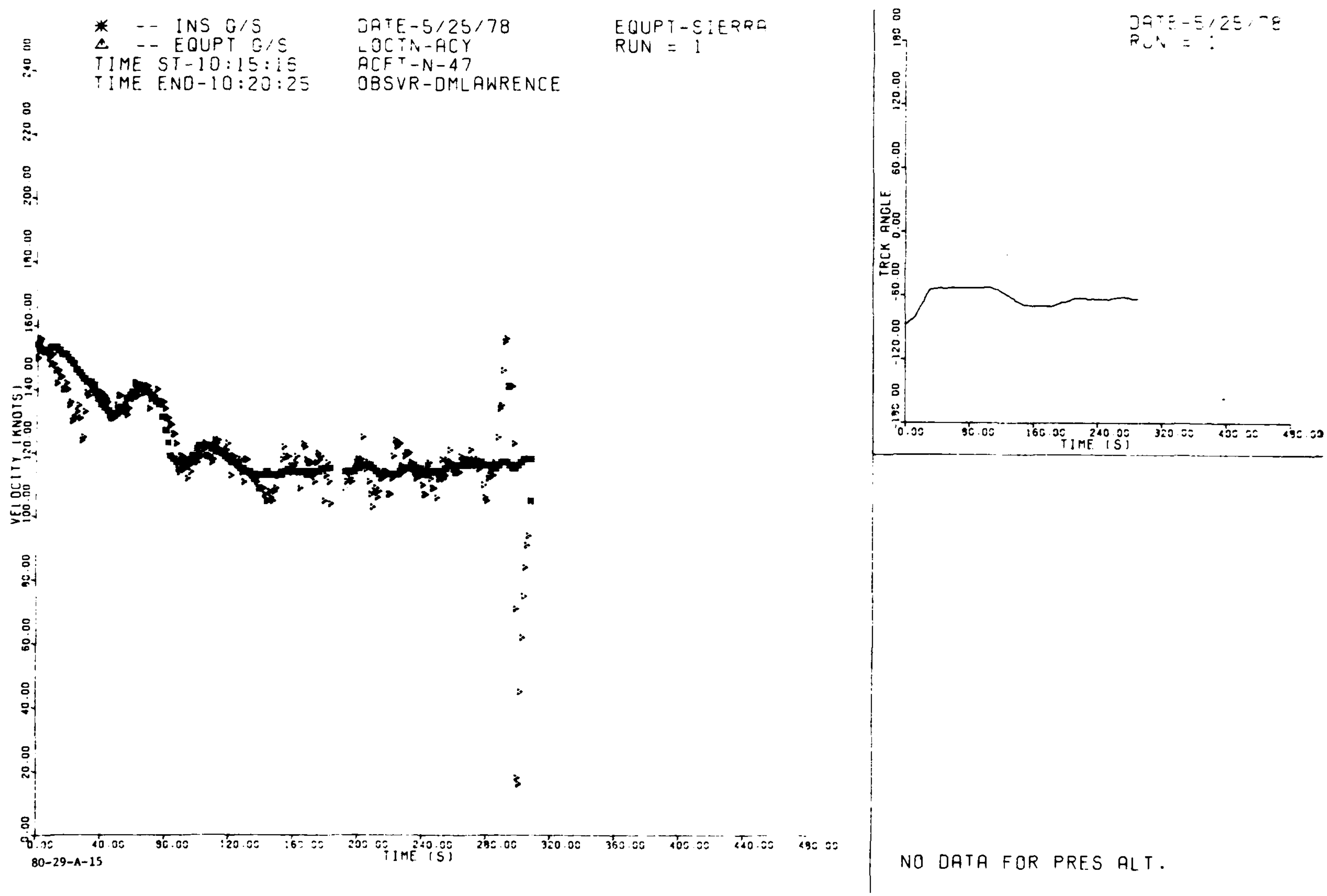


FIGURE A-15. DME AND INS GROUNDSPEED TIME HISTORY (5/25/78, ATLANTIC CITY, TIME), RUN 1

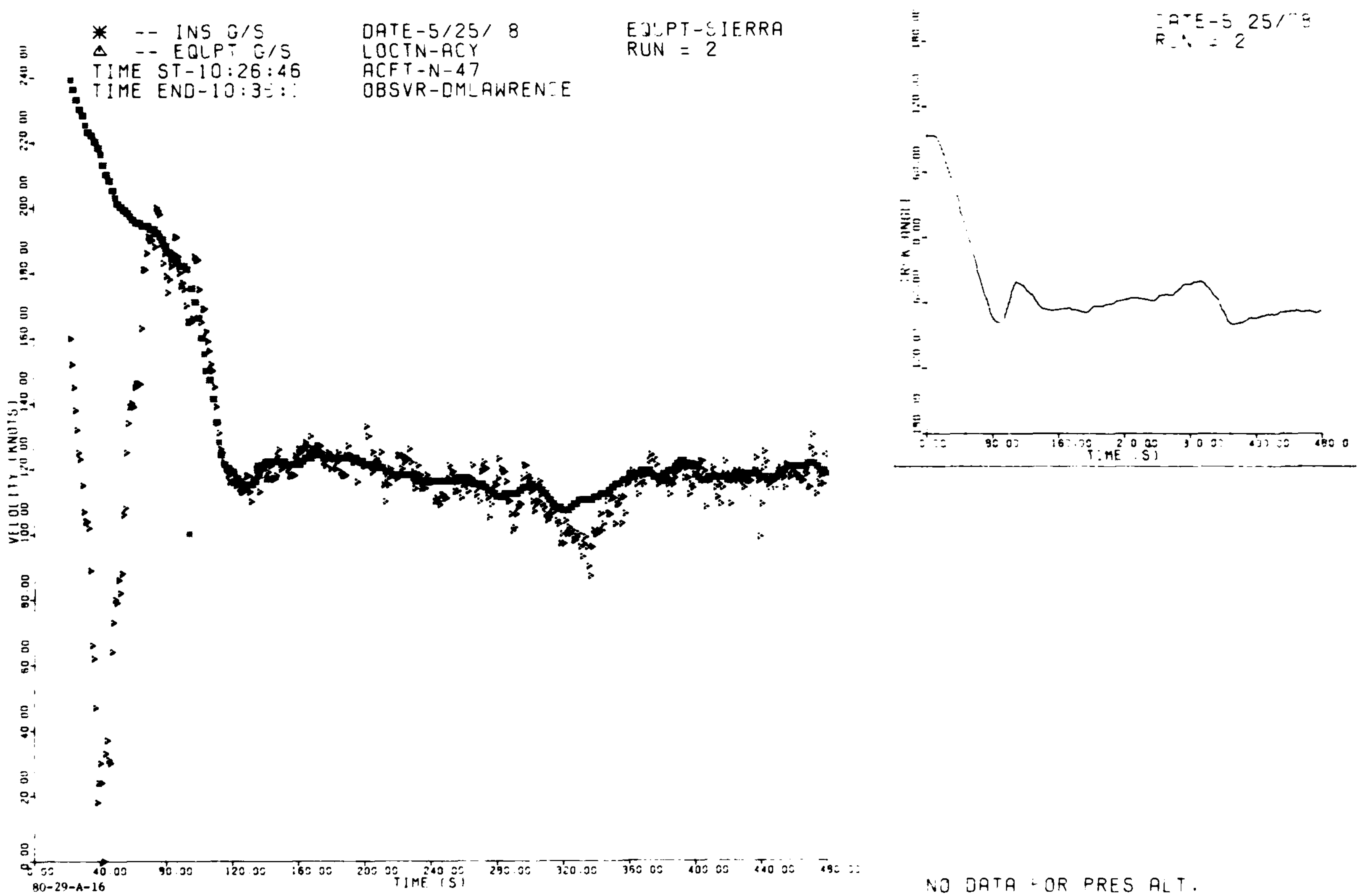


FIGURE A-16. DME AND INS GROUNDSPEED TIME HISTORY (5/25/78, ATLANTIC CITY, TIME), RUN 2

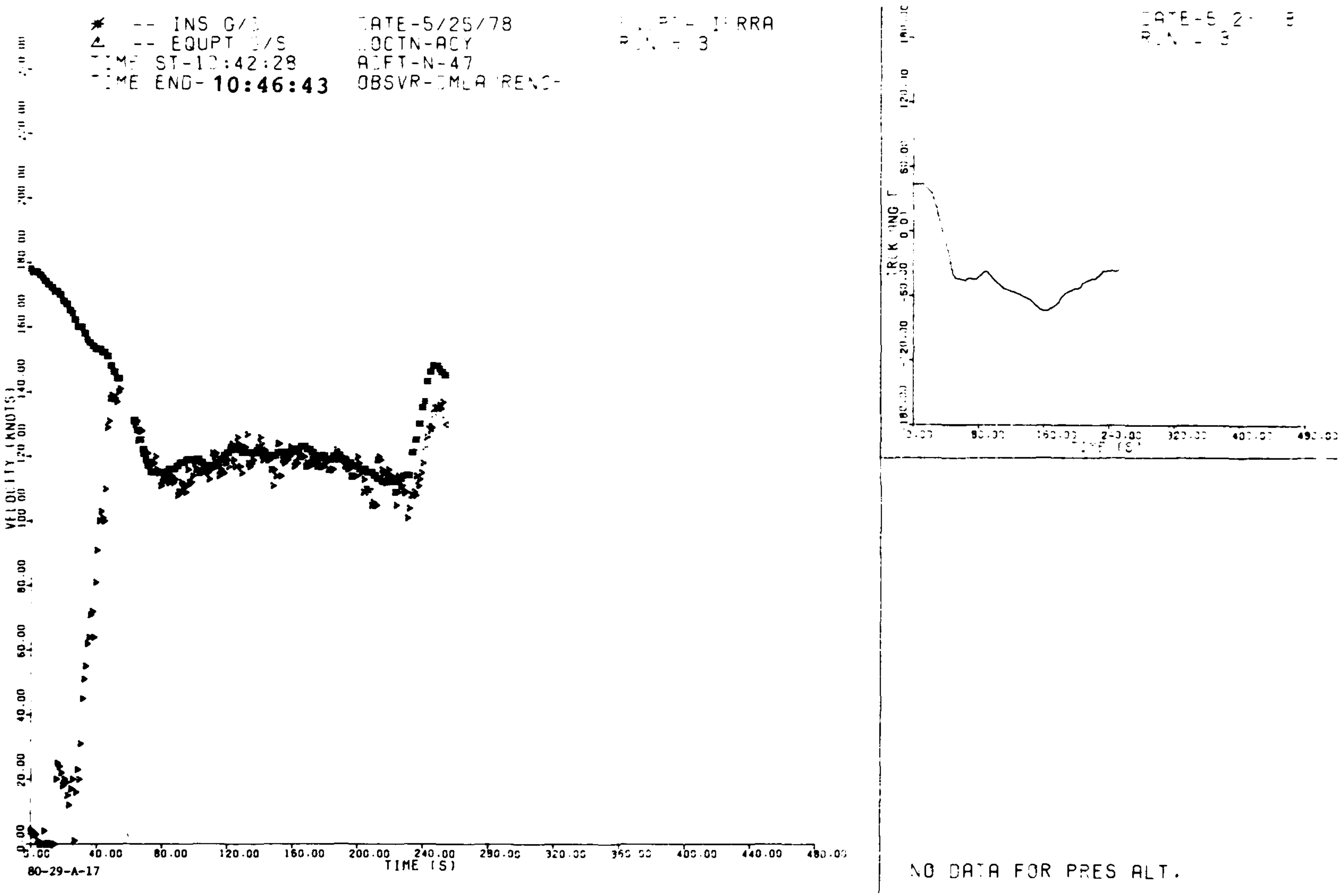


FIGURE A-17. DME AND INS GROUNDSPEED TIME HISTORY (5/25/78, ATLANTIC CITY, TIME), RUN 3

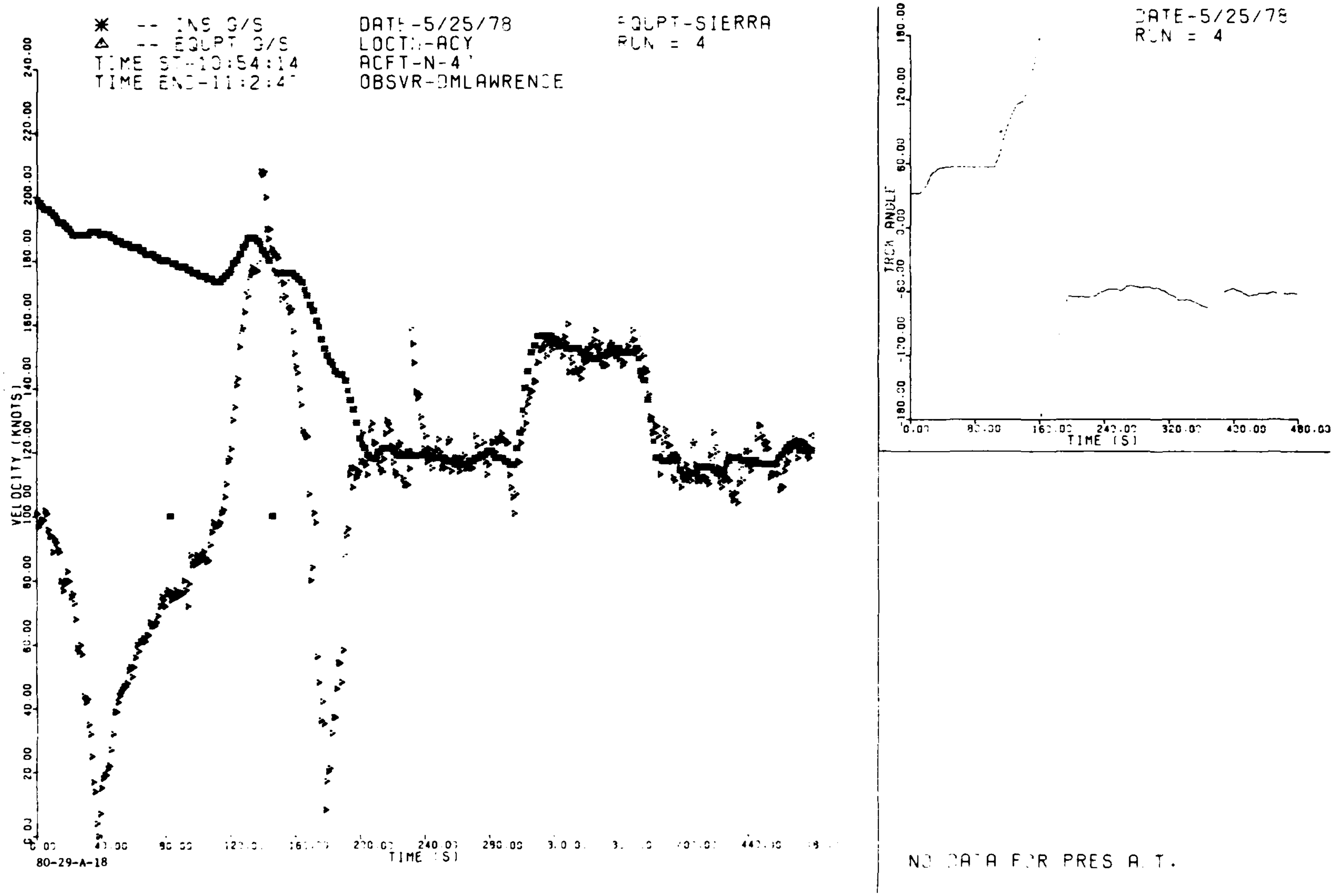
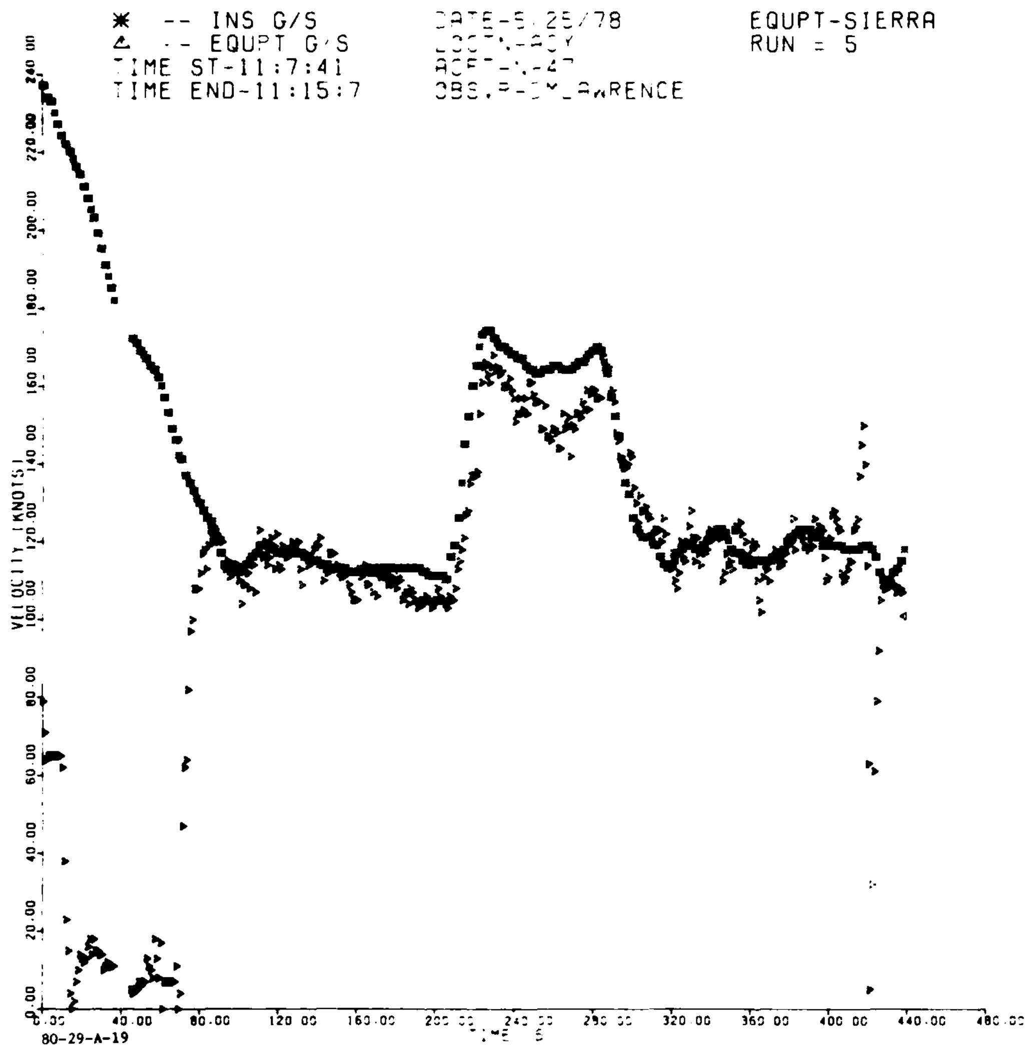


FIGURE A-18. DME AND INS GROUNDSPEED TIME HISTORY (5/25/78, ATLANTIC CITY, TIME), RUN 4



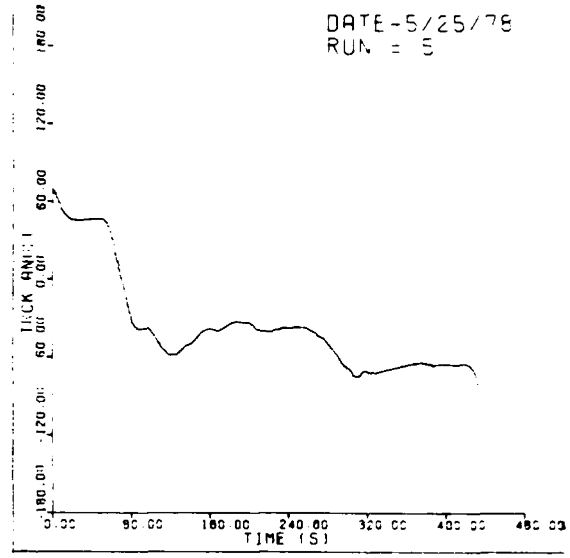


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FIGURE A-19. DME AND INS GROUNDSPEED TIME HISTORY (5/25/78, ATLANTIC CITY, TIME), RUN 5

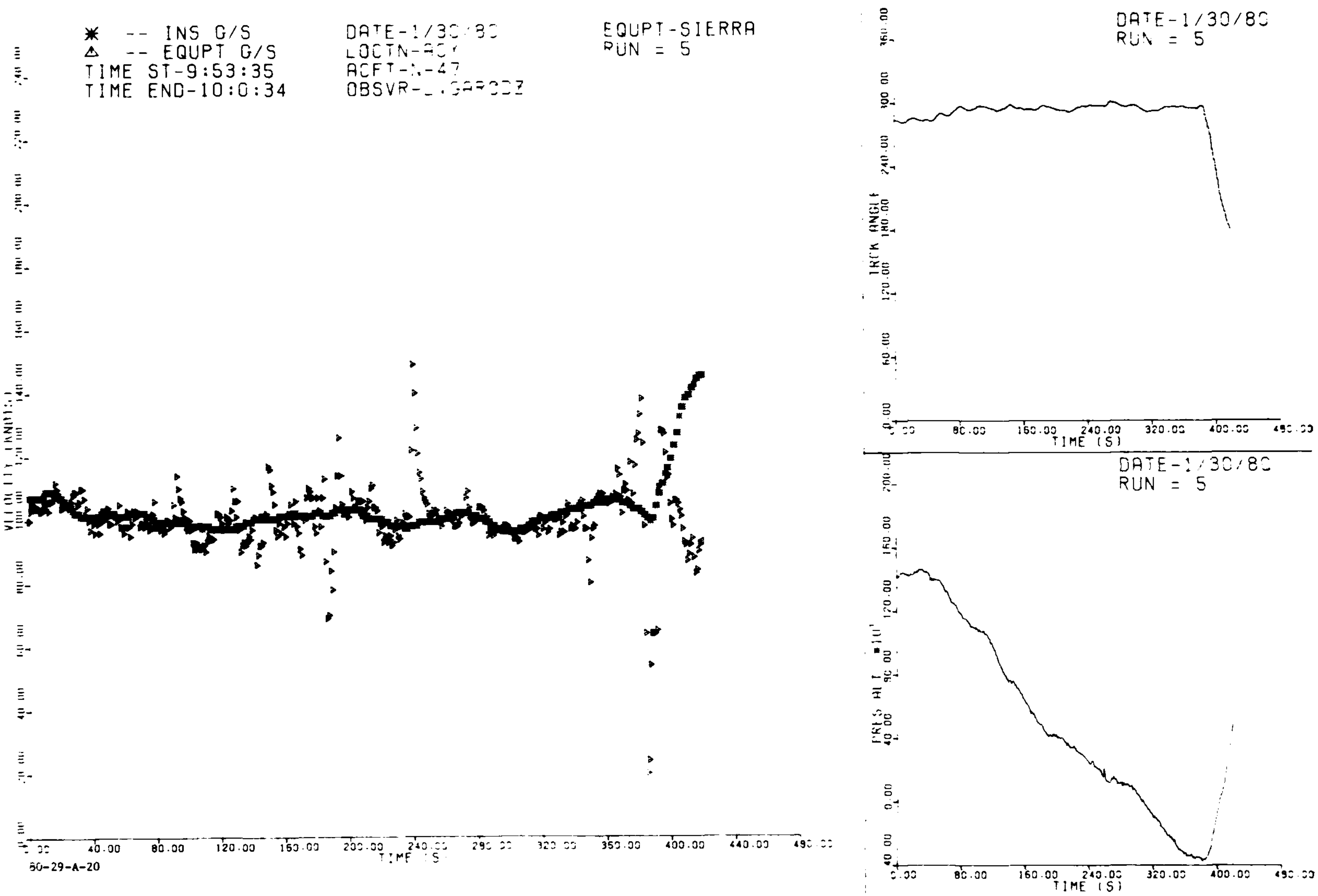


FIGURE A-20. DME AND INS GROUNDSPEED TIME HISTORY (1/30/80, ATLANTIC CITY, TIME), RUN 5

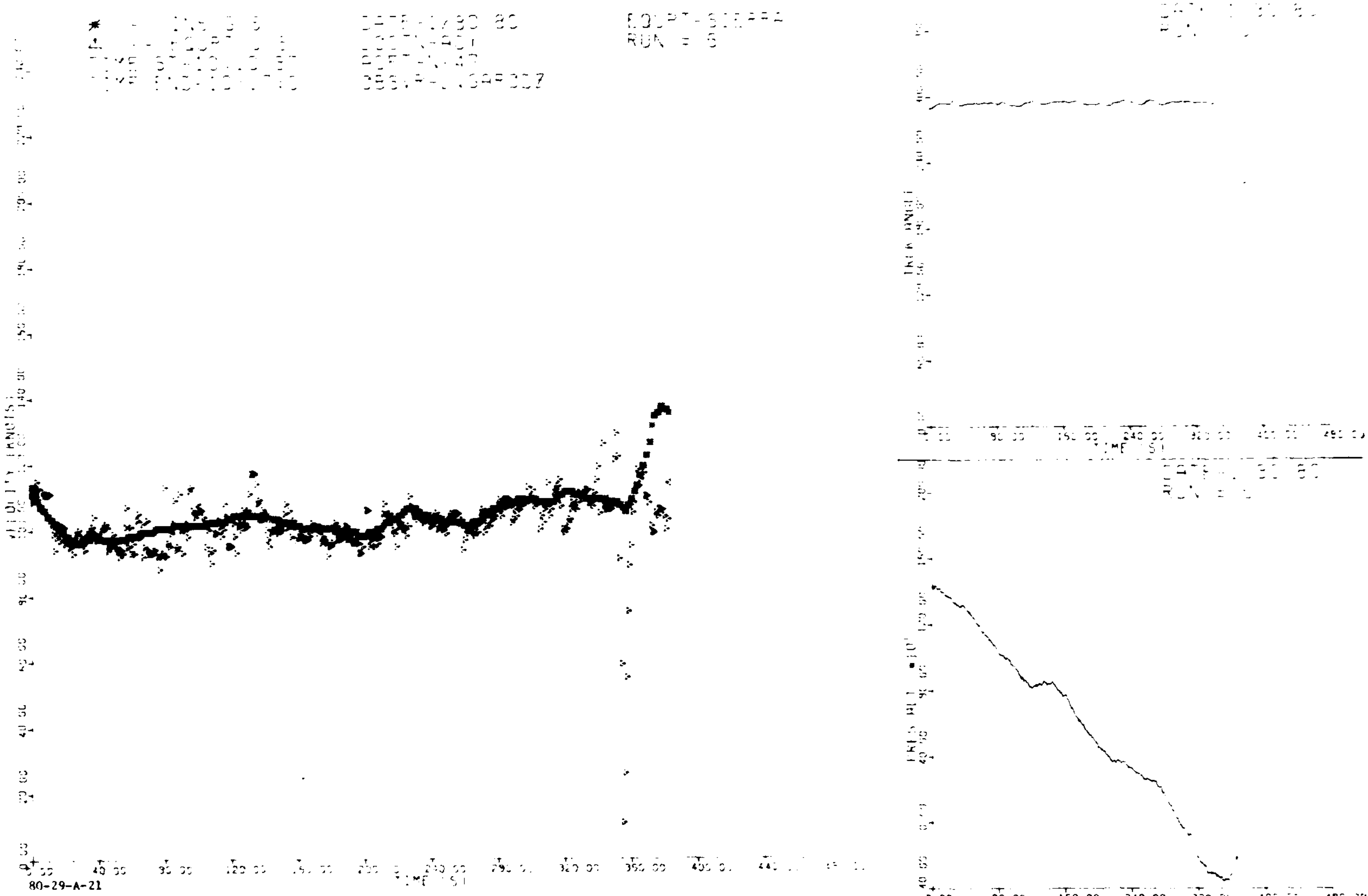


FIGURE A-21. DME AND INS GROUNDSPEED TIME HISTORY (1/30/80, ATLANTIC CITY, TIME), RUN 6

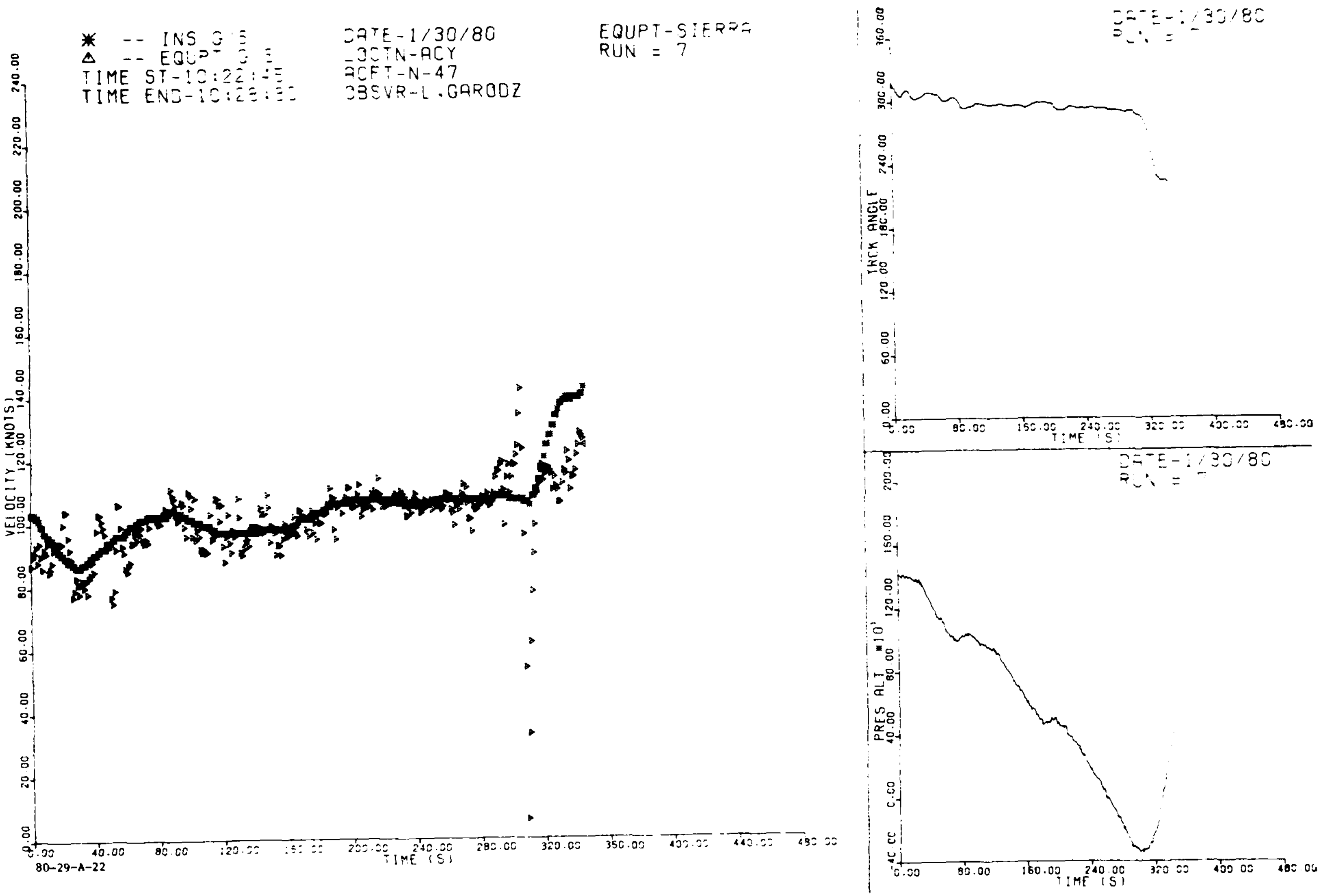


FIGURE A-22. DME AND INS GROUNDSPEED TIME HISTORY (1/30/80, ATLANTIC CITY, TIME), RUN 7

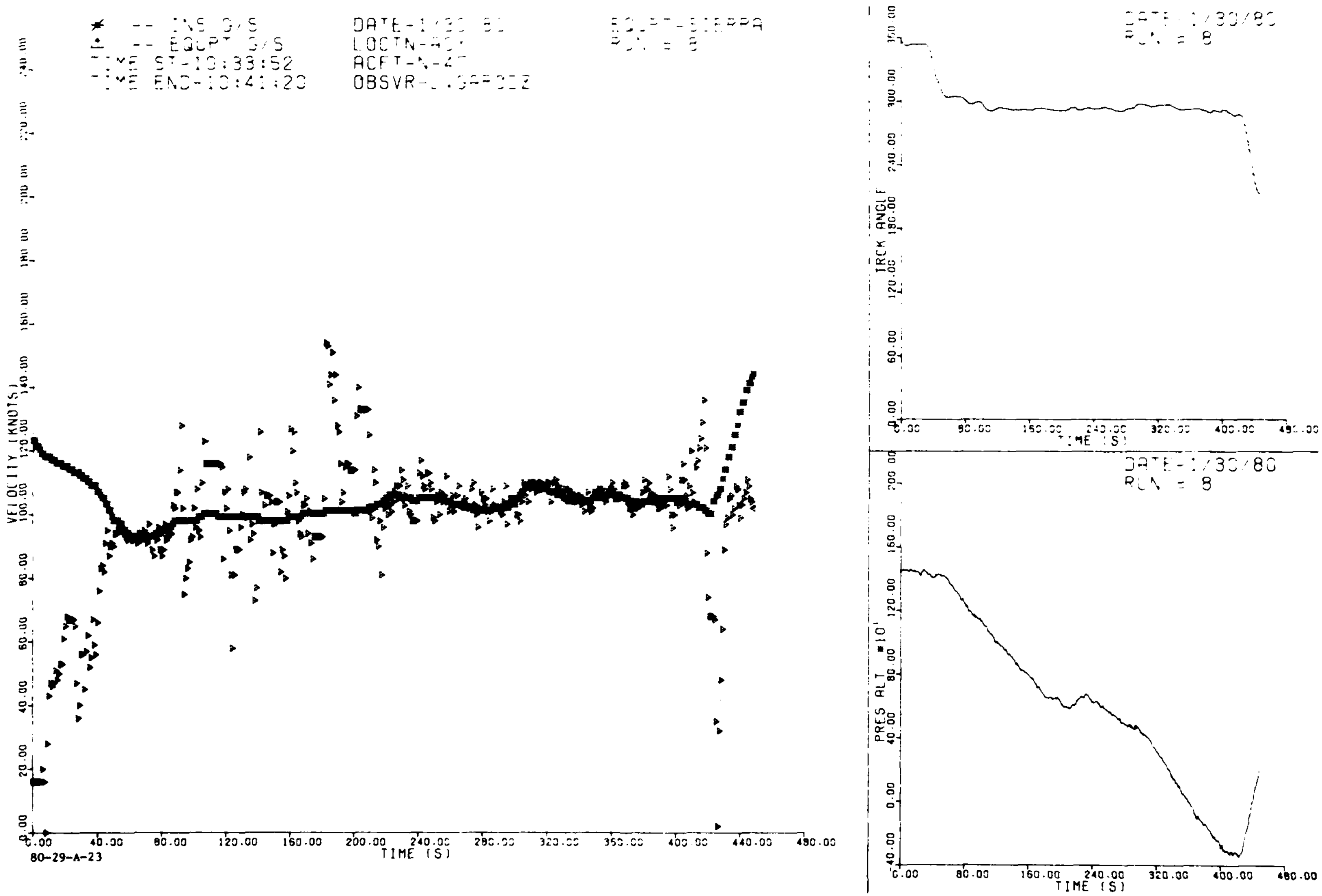


FIGURE A-23. DME AND INS GROUNDSPEED TIME HISTORY (1/30/80, ATLANTIC CITY, TIME), RUN 8

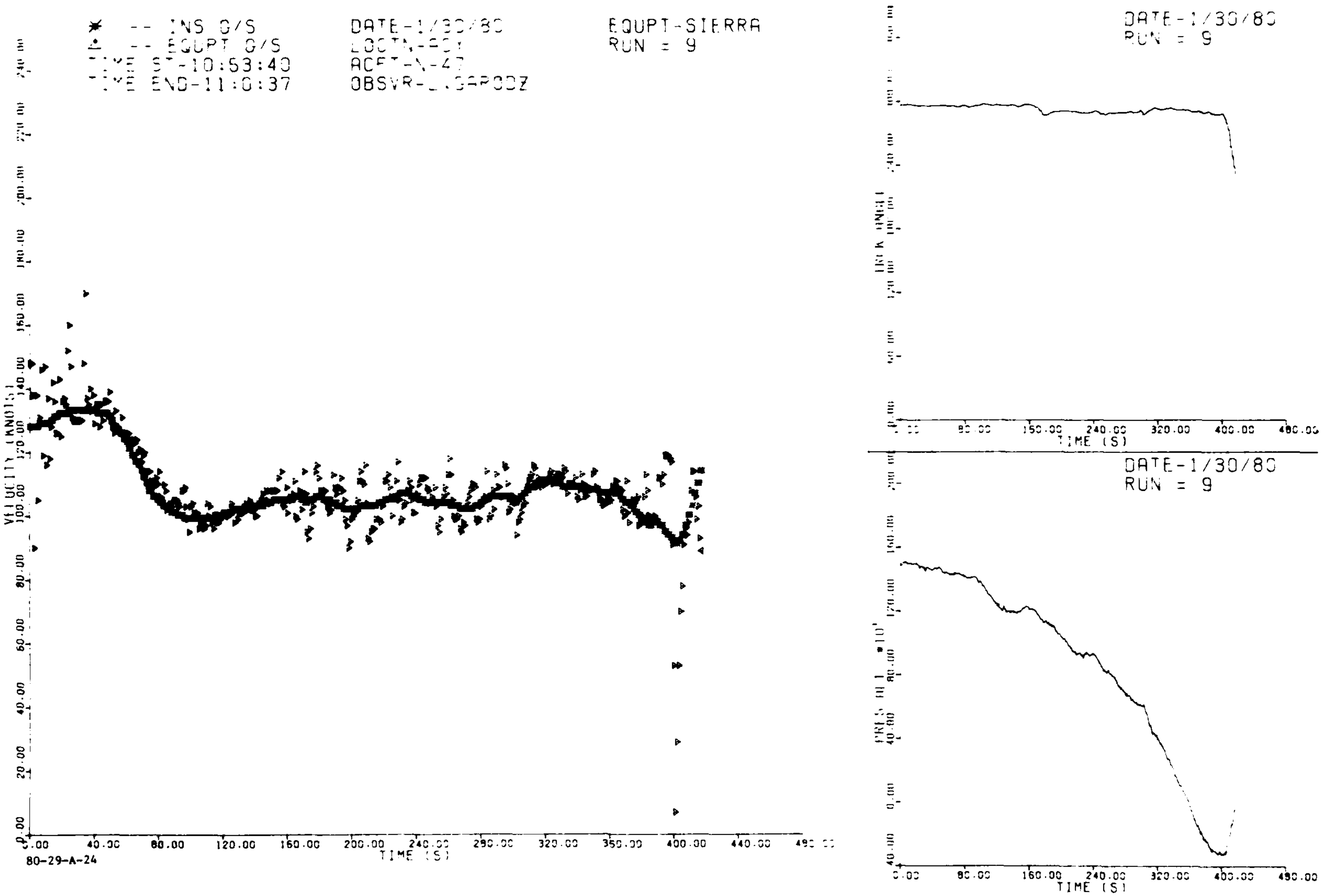
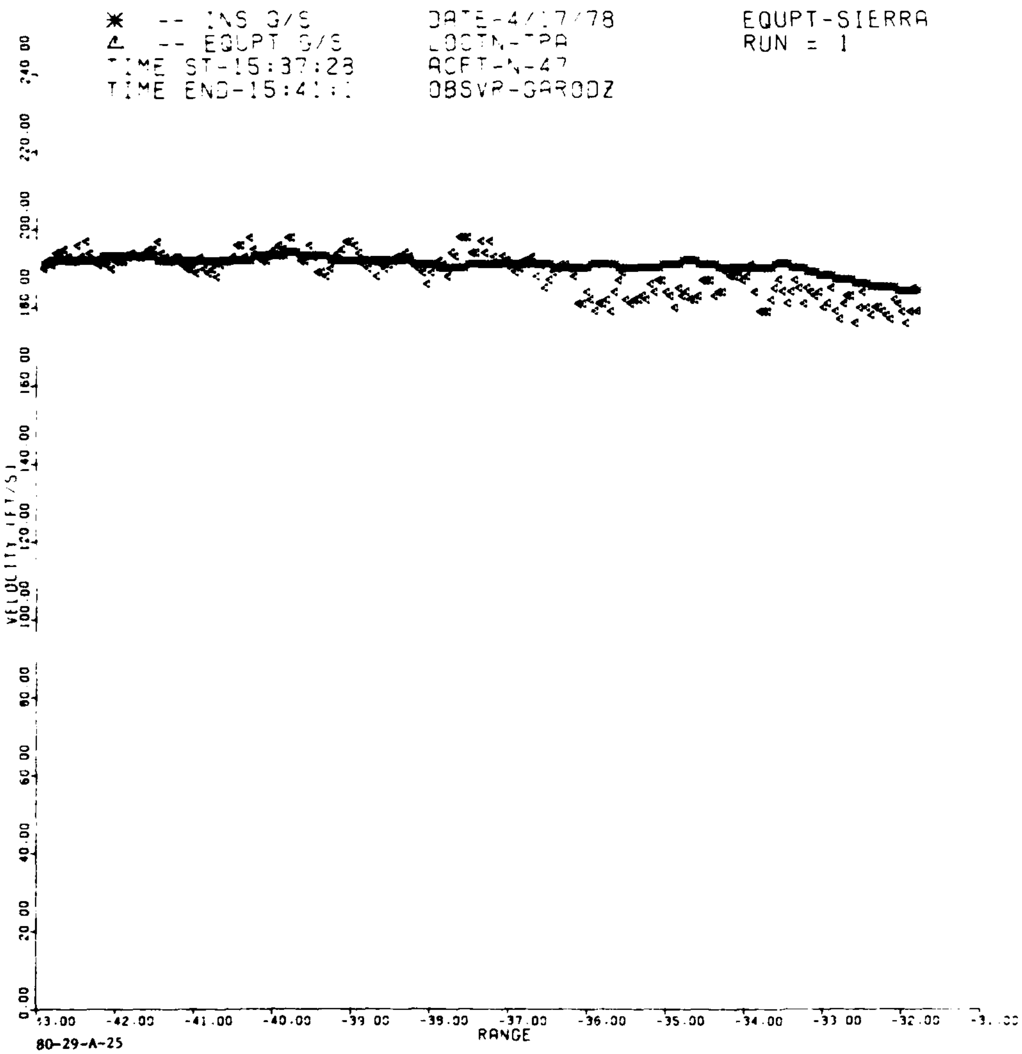


FIGURE A-24. DME AND INS GROUNDSPEED TIME HISTORY (1/30/80, ATLANTIC CITY, TIME), RUN 9



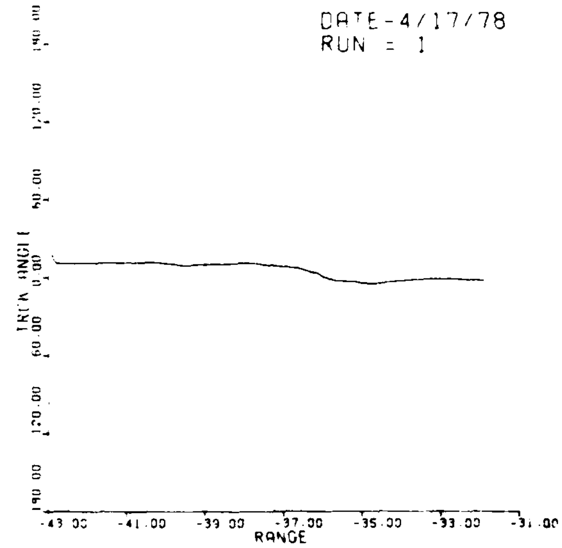


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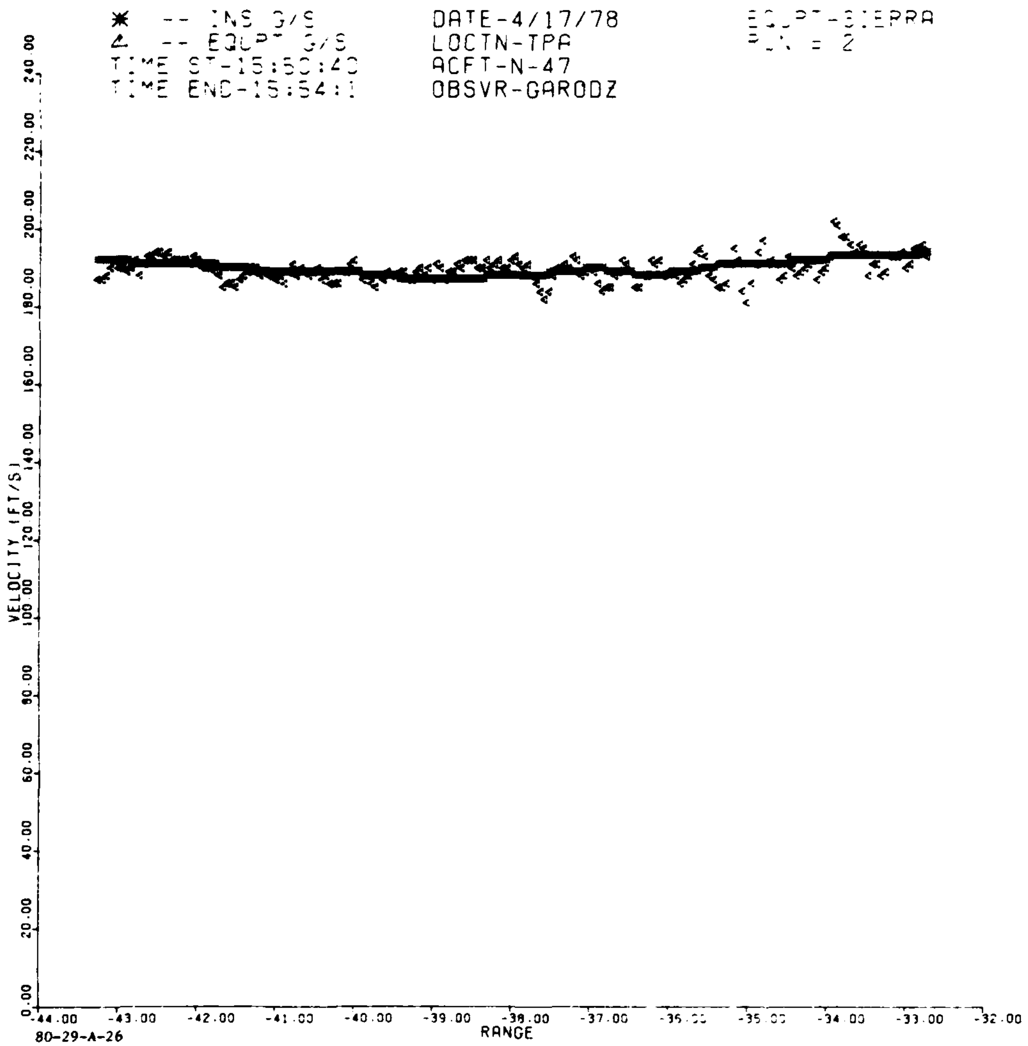
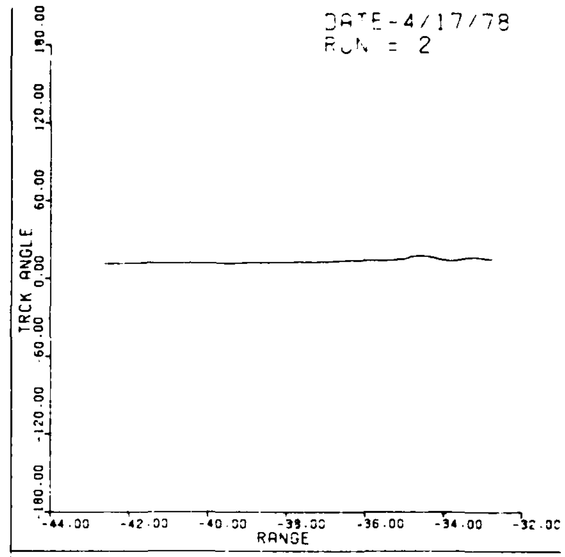
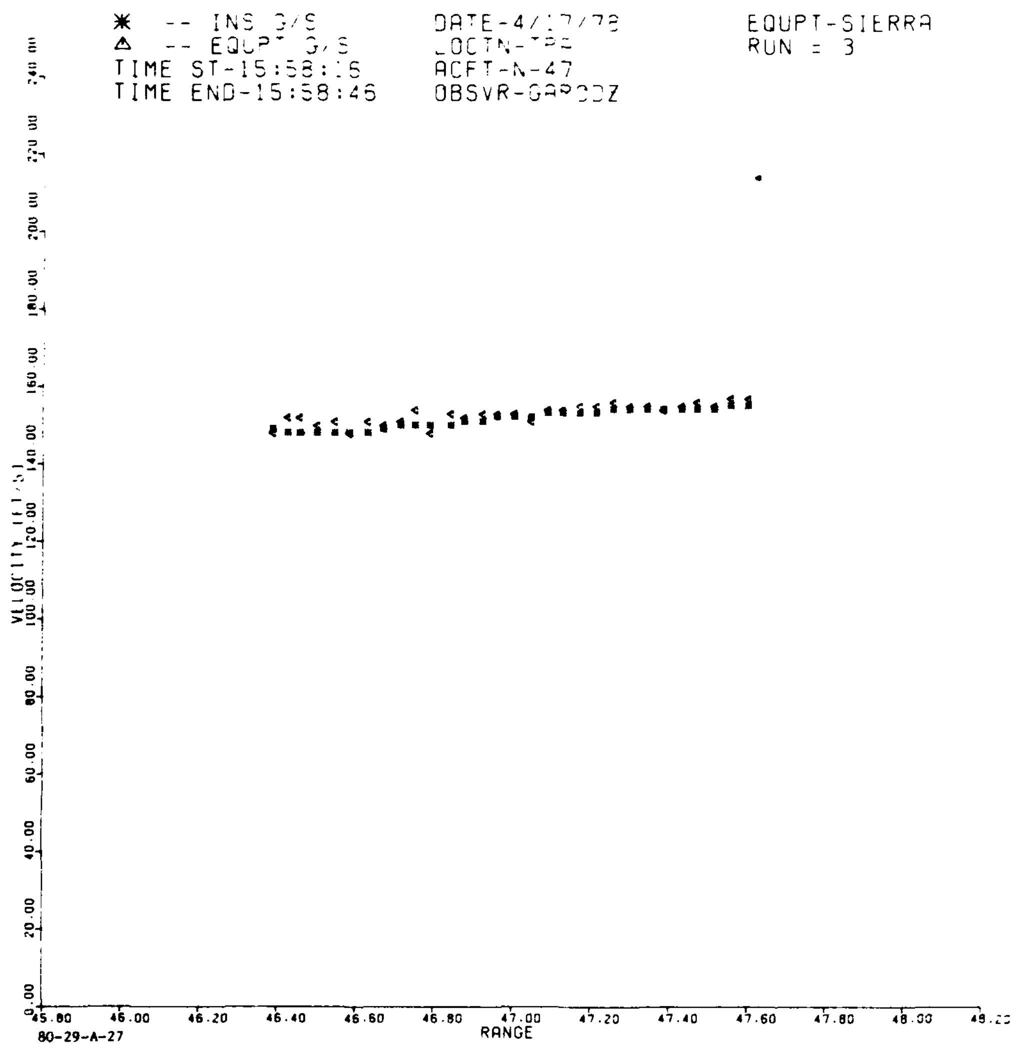
FIGURE A-25. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, RANGE), RUN 1





NO DATA FOR PRES ALT.

FIGURE A-26. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, RANGE), RUN 2



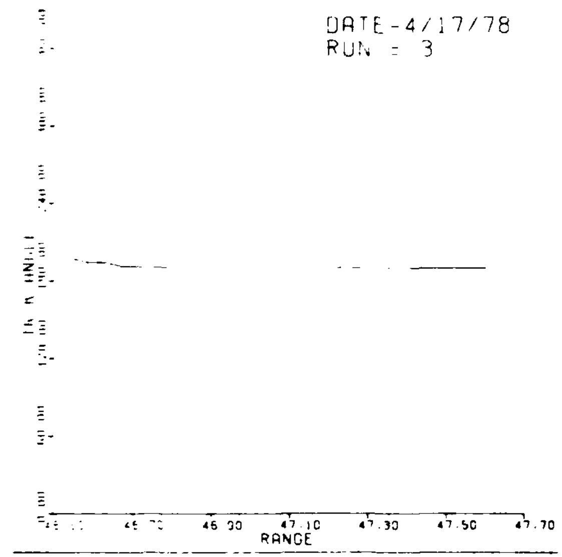


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FIGURE A-27. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, RANGE), RUN 3

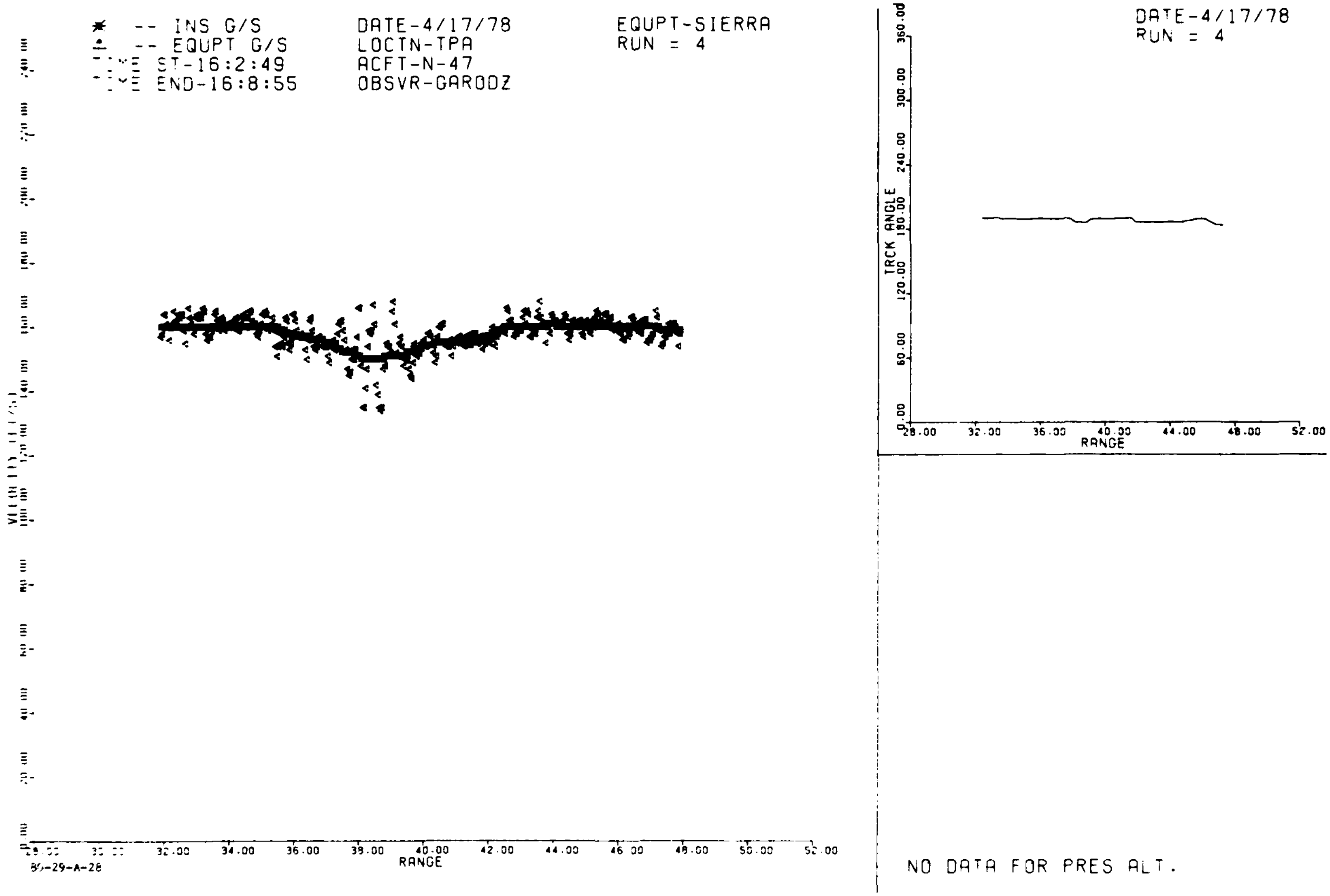


FIGURE A-28. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, RANGE), RUN 4

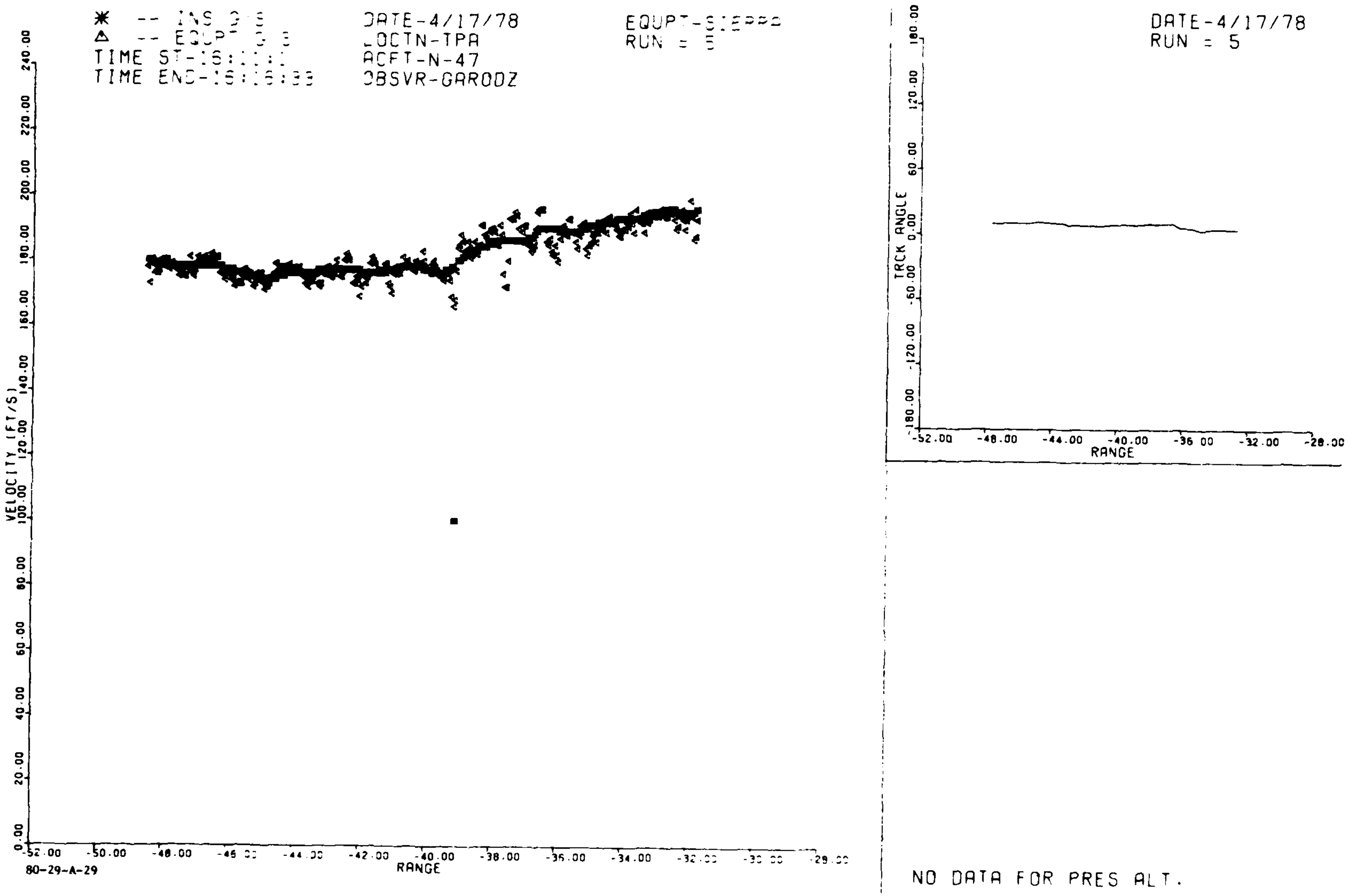


FIGURE A-29. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, RANGE), RUN 5

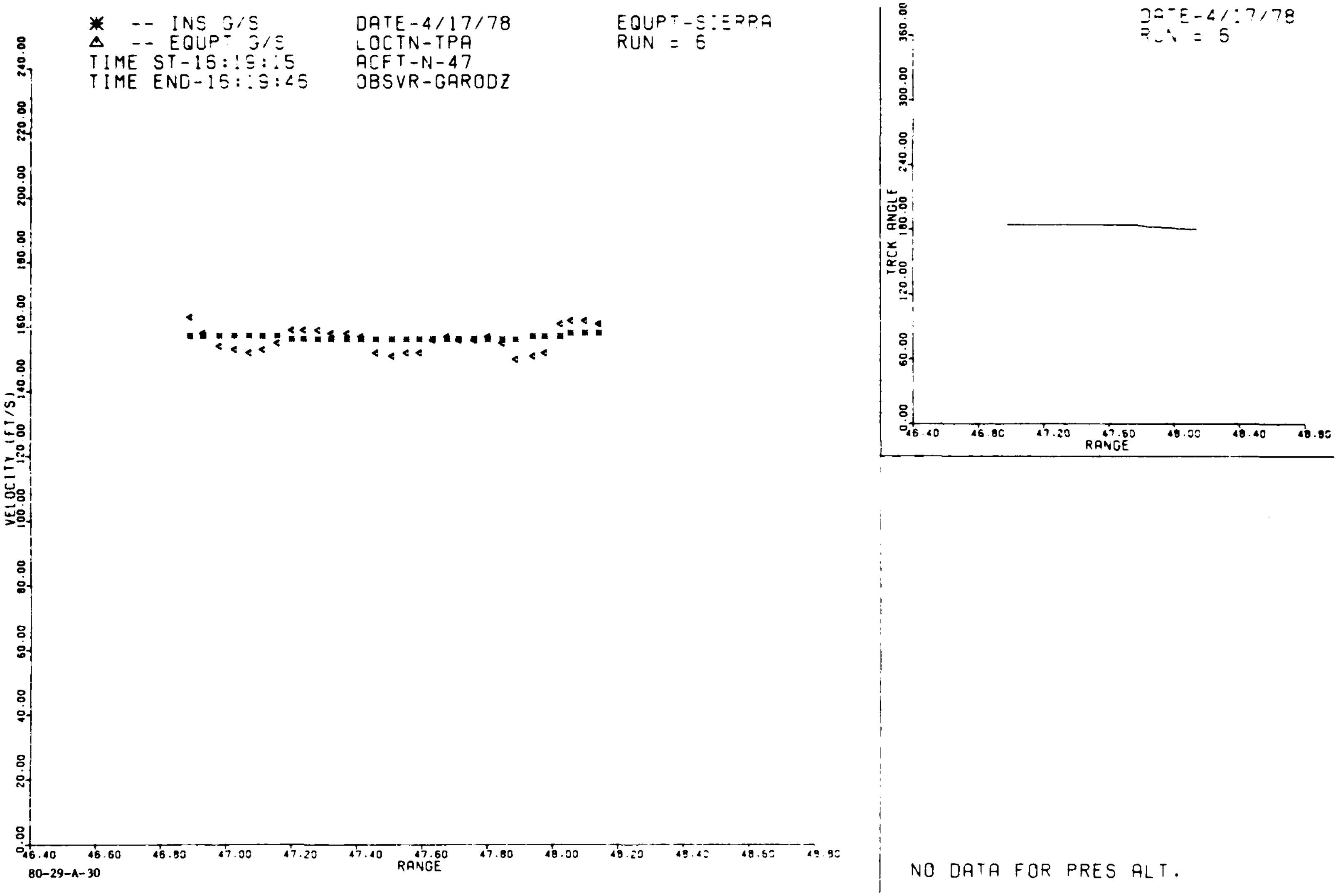
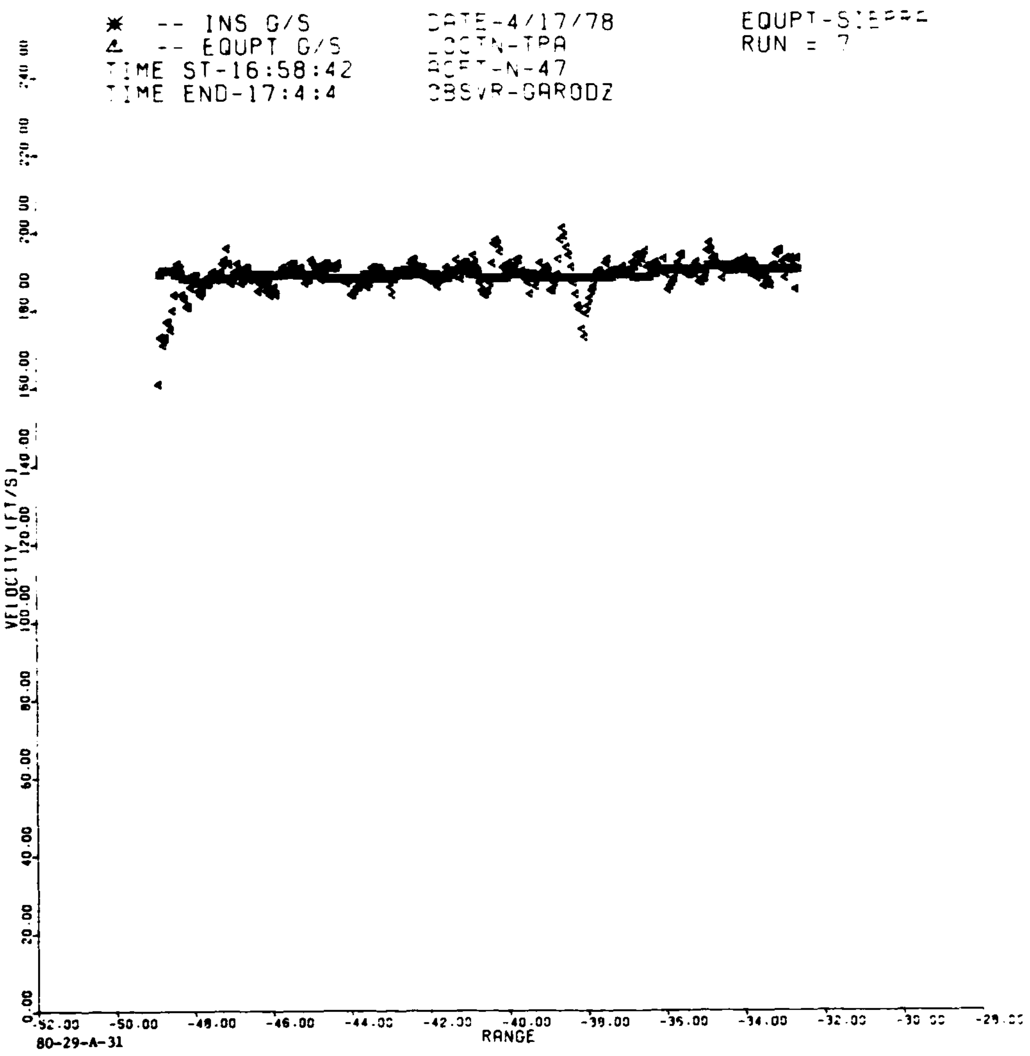


FIGURE A-30. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, RANGE), RUN 6



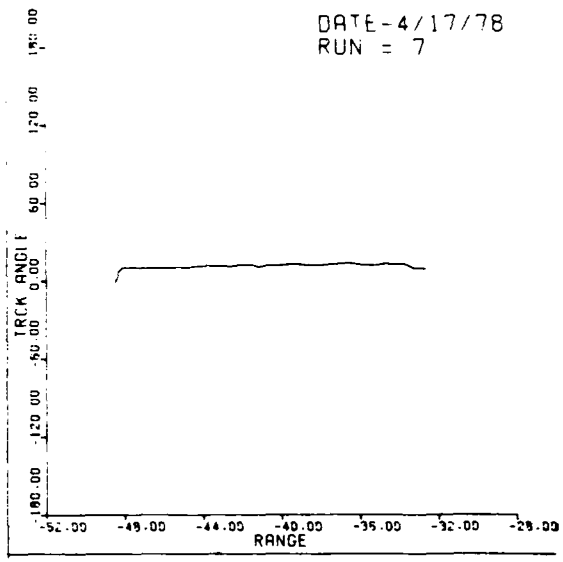


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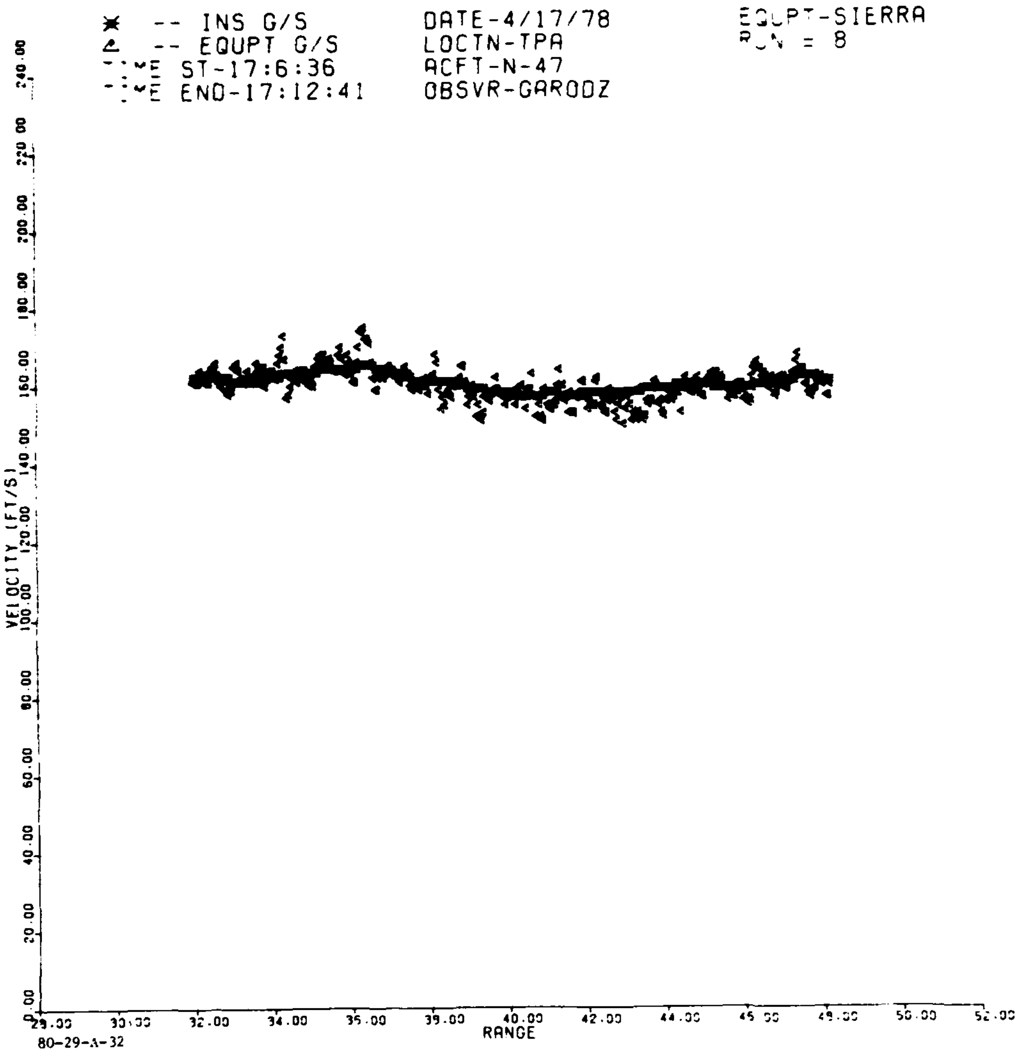
FIGURE A-31. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, RANGE), RUN 7



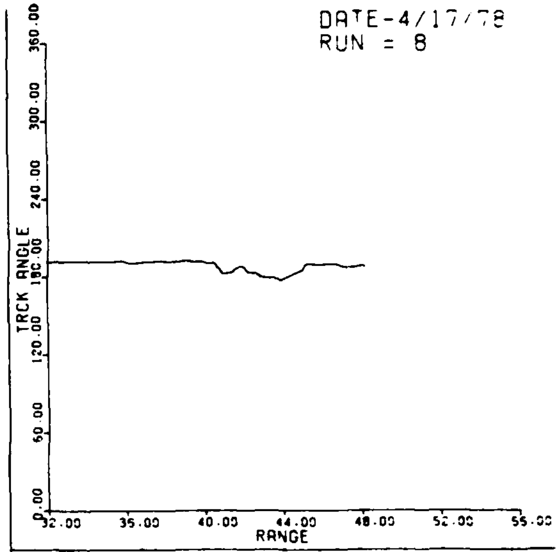


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FIGURE A-32. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, RANGE), RUN 8

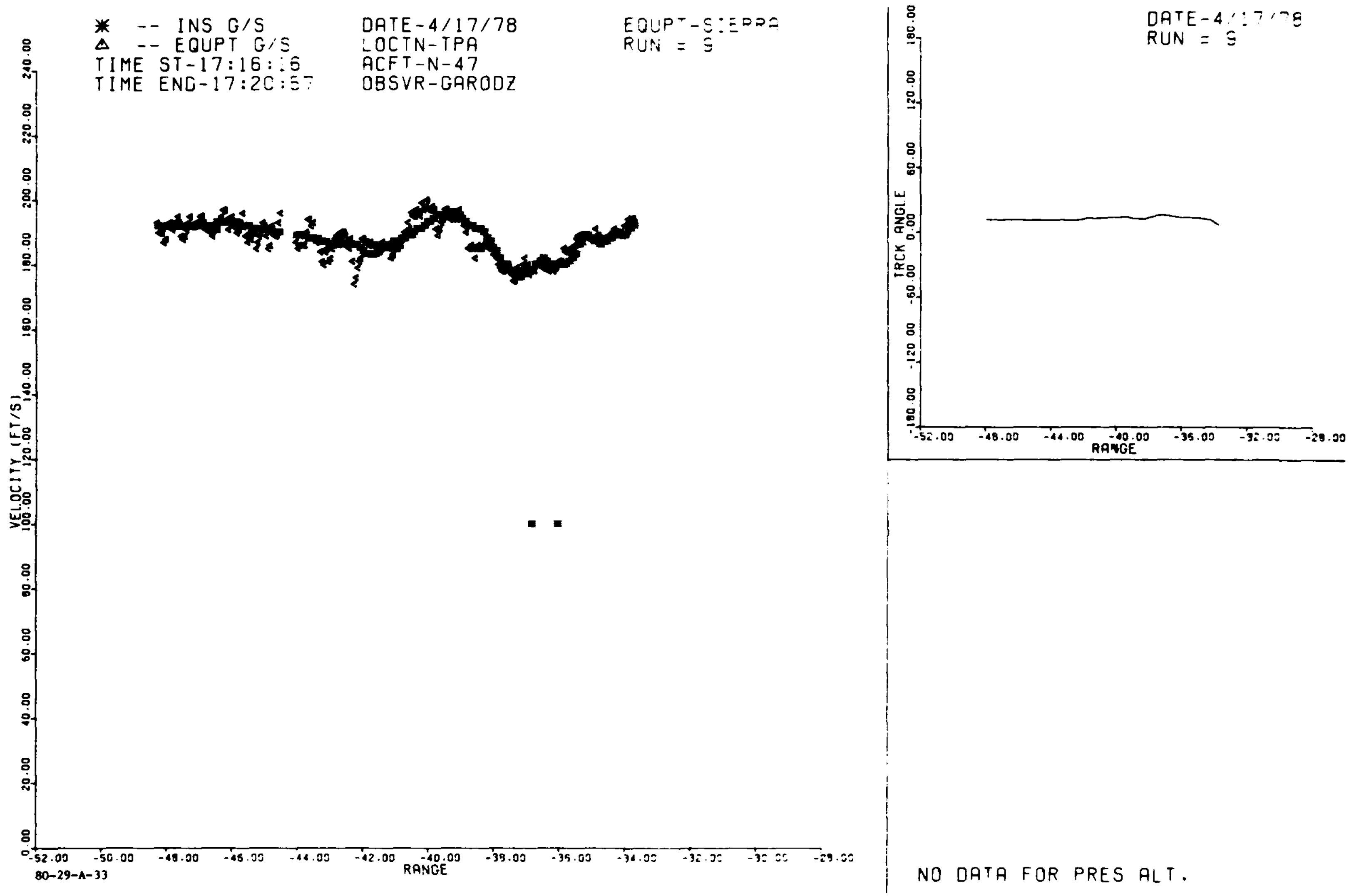
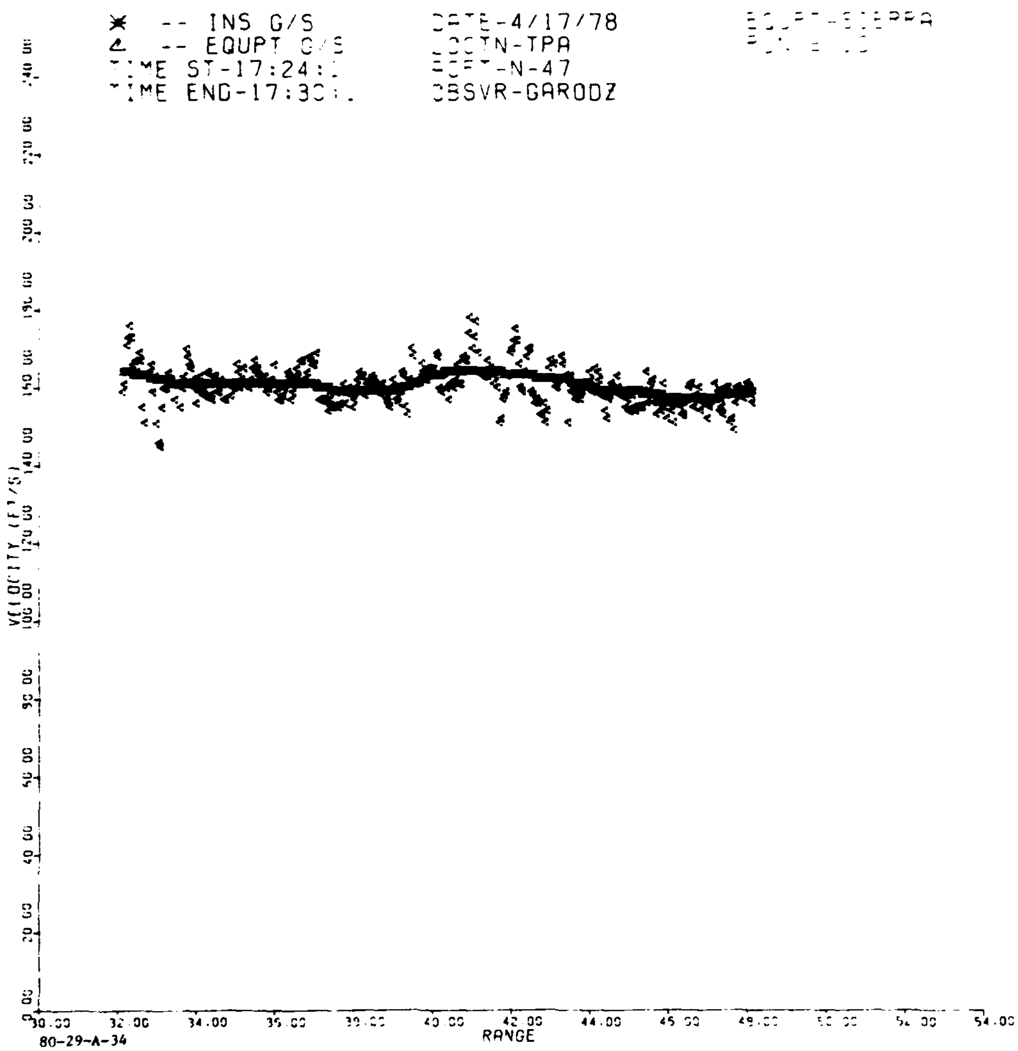
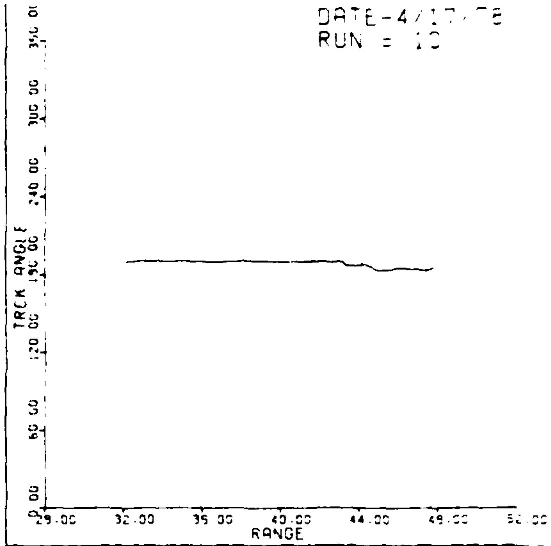


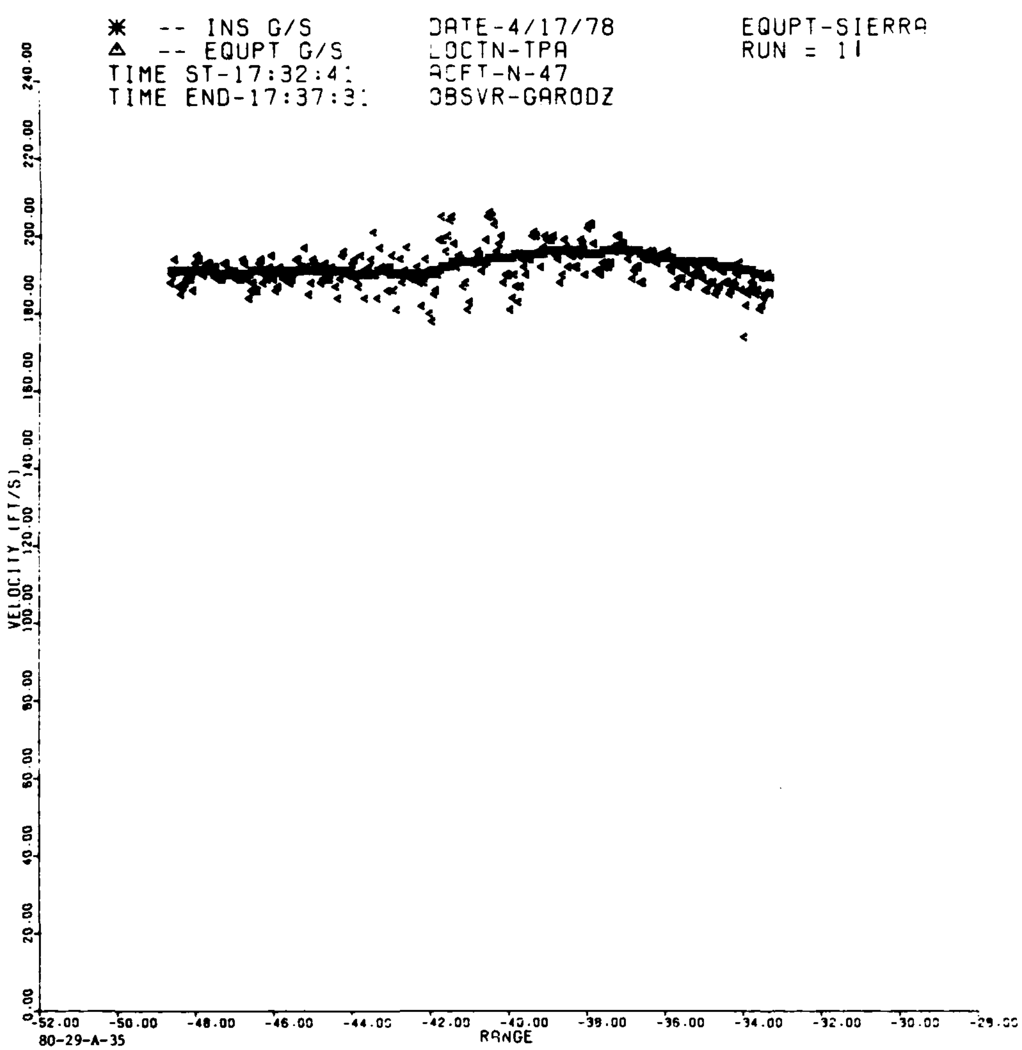
FIGURE A-33. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, RANGE), RUN 9

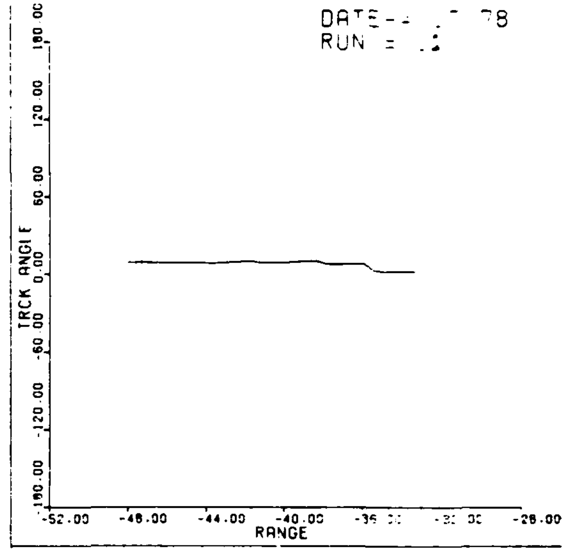




NO DATA FOR PRES ALT.

FIGURE A-34. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, RANGE), RUN 10





NO DATA FOR PRES ALT.

FIGURE A-35. DME AND INS GROUNDSPEED TIME HISTORY (4/17/78, TAMPA, RANGE), RUN 11

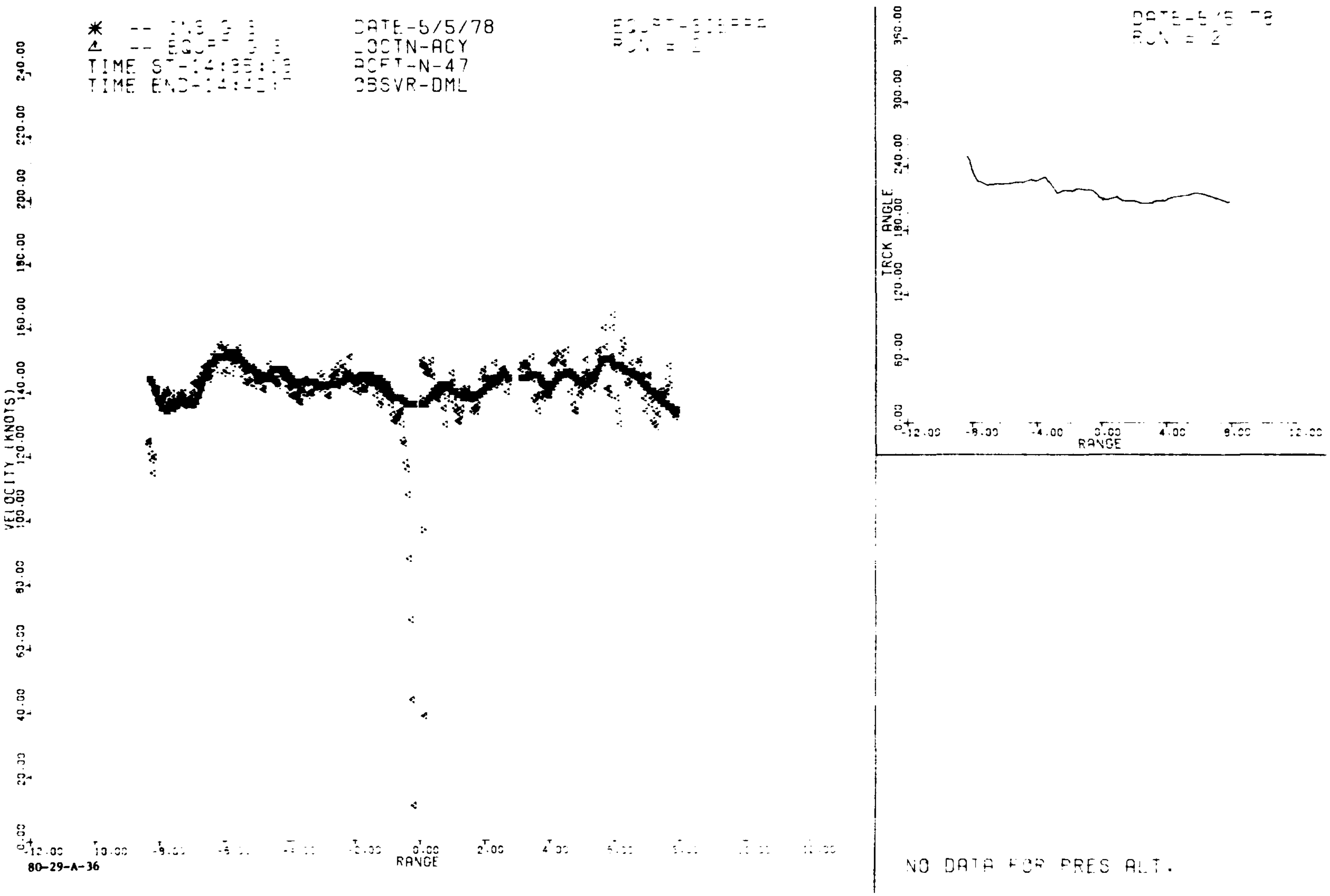


FIGURE A-36. DME AND INS GROUNDSPEED TIME HISTORY (5/5/78, ATLANTIC CITY, RANGE), RUN 2

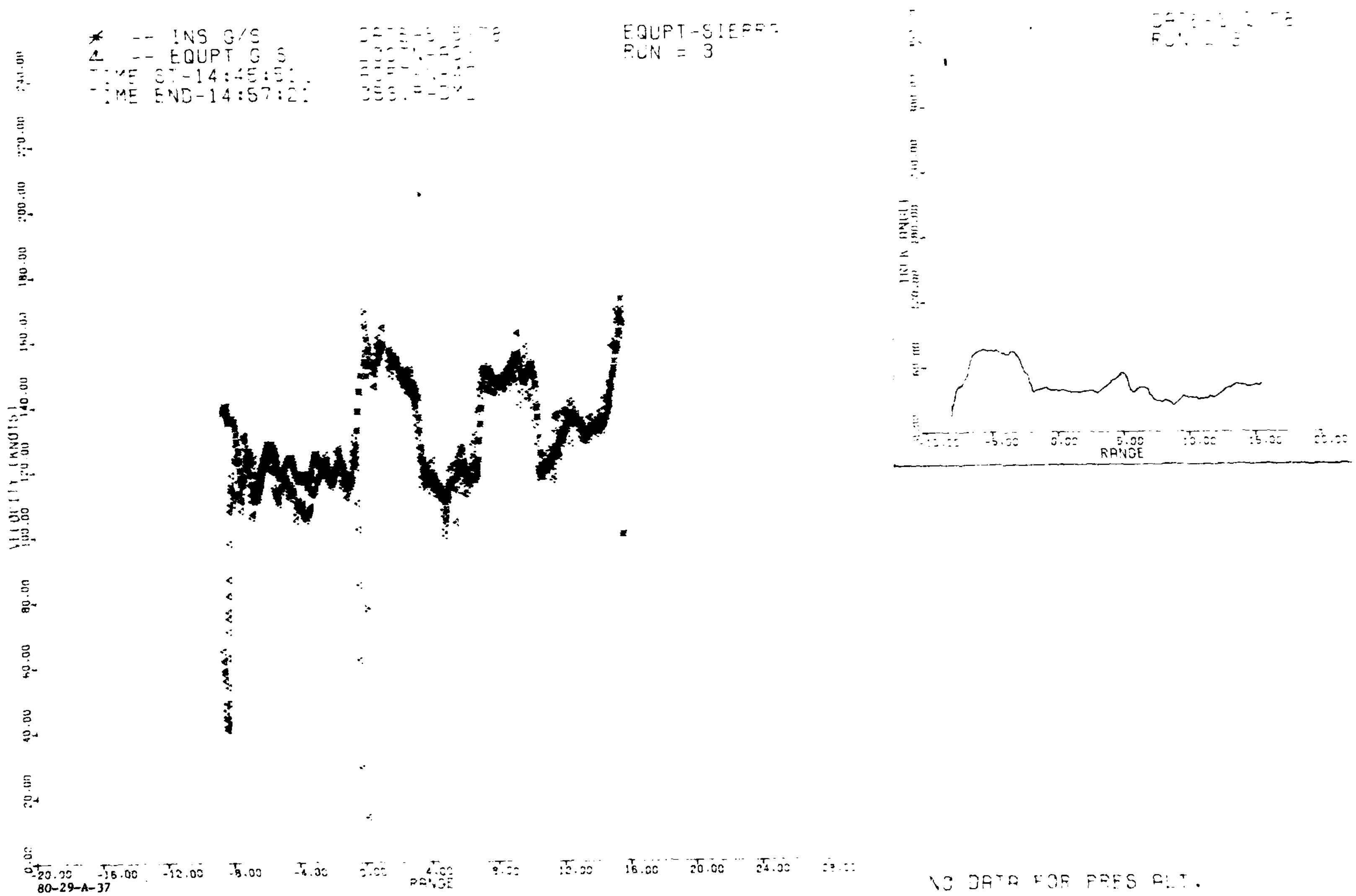


FIGURE A-37. DME AND INS GROUNDSPEED TIME HISTORY (5/5/78, ATLANTIC CITY, RANGE), RUN 3

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